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DISSERTATION

**AUTOMATIC GENERATION OF OPTIMAL PROCESS PLANS FOR
MACHINED PARTS FROM 3D SOLID MODELS**

Submitted by

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In partial fulfillment of the requirements

for the degree of Doctor of Philosophy

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Fort Collins, Colorado

Fall 1999

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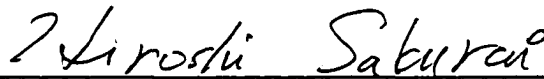
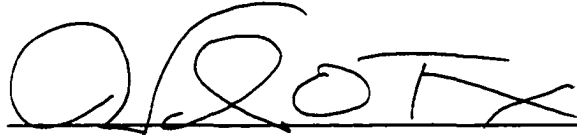
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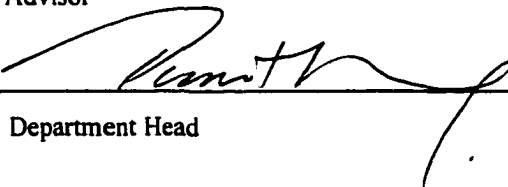
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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY YOONHWAN WOO, ENTITLED "AUTOMATIC GENERATION OF OPTIMAL PROCESS PLANS FOR MACHINED PARTS FROM 3D SOLID MODELS," BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

AUTOMATIC GENERATION OF OPTIMAL PROCESS PLANS FOR MACHINED PARTS FROM 3D SOLID MODELS

The application of computers to the product design and manufacturing process brought changes in the traditionally separate disciplines of design and manufacturing. The usage of computer-aided design (CAD) covers a variety of applications such as stress analysis as well as designing, and computer-aided manufacturing (CAM) replaced the need of the coordinated interactions of skilled machinist. Though such advancements have been made in CAD/CAM, however, integration of them has not been fully achieved. Automated process planning has been considered as a key to the CAD/CAM integration.

In this dissertation, a method to automatically generate the optimal process plan for a machined part is presented. This method first recognizes machining features from the solid model of the part by recursive volume decomposition (RVD). An RVD method has been developed in this research to solve the computational complexity of the earlier volume decomposition method. This RVD method quickly decomposes the delta volume into volumes called maximal volumes (MV), and then transforms the MVs into machining features. Next, alternative process plans are generated by sequencing the features in different orders. In doing so, various machining rules are used so that only promising plans can be generated. Finally, the machining time for each plan is estimated

and the plan that requires the least period of machining time is selected as the optimal plan.

The results of case studies are presented to attest the usefulness of the proposed method. Overall, the performance of the proposed method demonstrates its potential for integration of CAD and CAM.

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Dedicated to
my father, Jungwook Woo.
and my mother, Eunghui Lee.

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Chapter 1

Introduction

1.1 Research Objective

The objective of this research is to develop a systematic method to automatically generate optimal process plans for machined parts from the solid models of the parts. Here the objective function of the optimization is the shortest machining time.

1.2 Motivations

The application of computers to the product design and manufacturing process has brought changes in the traditionally separate disciplines of design and manufacturing. The usage of computer-aided design (CAD) covers a variety of applications such as stress analysis, mass property evaluation, and product visualization as well as designing. Computer-aided manufacturing (CAM), often represented by numerical-control (NC) machines, replaced the need of the coordinated interactions of skilled machinists.

Though such advancements have been made in CAD/CAM, there has been a lack of achievement in integrating them. One difficulty in integrating CAD/CAM arises from the fact that design and manufacturing require different models of the same part. Once a mechanical part is designed with a CAD system, it currently needs machinists to transform in their minds the design into a model suitable for manufacturing, and based on

the model they perform process planning for the part. In doing so, they try to optimize machining time. Here process planning is an activity of selecting and sequencing manufacturing operations needed to produce given parts or products. For example, a process plan for machining contains information about machining operations, tools to be used, setups and other information related to machining. Process planning for machining has not been automated yet, and it has been an obstacle in CAD/CAM integration.

Two major benefits can be expected from automating process planning. First, automated process planning can quickly generate efficient plans, and subsequently it can reduce NC programming time and increase machining efficiency. Currently, although commercial NC programs can automatically generate cutter path for machining a feature, they still need machinists to input information about geometry of features and sequences of the features resulting from their process planning. Process planning performed by a machinist, however, depends on his preferences as well as expertise. Thus it does not necessarily result in the best process plan. Rather, it tends to be time-consuming and error-prone, and it takes a long time for machinists to acquire necessary knowledge.

Second, automated process planning can help designers perform design for manufacturing (DFM). Thus designers can focus more on functionality of designs than on manufacturing. In fact, designers lack knowledge of manufacturing, which often causes manufacturing problems and redesigns of the part. With automated process planning, manufacturability of designs can be quickly evaluated in the design phase. Therefore, similar to other design-analysis tools such as FEA, automated process planning can help designers reduce time spent on correcting manufacturing problems, and it can increase efficiency of product development.

1.3 Research Scope

1.3.1 Completeness

Process plans comprise information needed to produce the parts from given designs. The information includes setup sequence, fixtures to be used for setups, machining sequence, cutters to be used, spindle speeds, feed rates, etc. This research, however, is focused on only setup sequence, machining sequence, and cutters to be used, which are the most important information needed to produce parts.

1.3.2 Optimization

Optimization always requires an objective, constraints, and assumptions. Even for the same objective, optimizations with different constraints and assumptions may end up with different results. Process plans that are generated by the method of this research are optimal only within the constraints specified and the assumptions postulated in this dissertation. The constraints and assumptions in this dissertation are believed to be common and reasonable in process planning. The assumptions are listed below and the constraints are listed where they are applied.

1.3.3 Assumptions

The following assumptions are postulated in generating the optimal process plans:

- Parts are prismatic so that they can be machined with 3-axis machining centers.
- Workpiece can be always securely fixed.
- The machining centers have automatic tool exchangers.
- Raw material is pre-squared so that it provides datum features.

- A part is created with minimum number of setups.
- A part is created only with drills and flat end-mill cutters.

1.4 Outline of the Research Approach

The approach of this research consists of two major steps: feature recognition and plan generation. Figure 1.1 shows the overview of the research approach to the optimal process plan generation.

(1) Feature Recognition

In this step, machining features, called maximal features, are recognized by:

1. generating delta volume by subtracting the part from the raw material.
2. decomposing the delta volume into volumes called maximal volumes, and
3. transforming the maximal volumes into machining features.

(2) Plan Generation

In this step, the optimal process plan for the part is generated by:

1. determining the machining parameters for maximal features such as minimum number of setup directions and maximum cutter sizes for machining features,
2. identifying precedence constraints on sequencing features using machining rules.
and
3. sequencing the maximal features so that the sequence requires the shortest machining time.

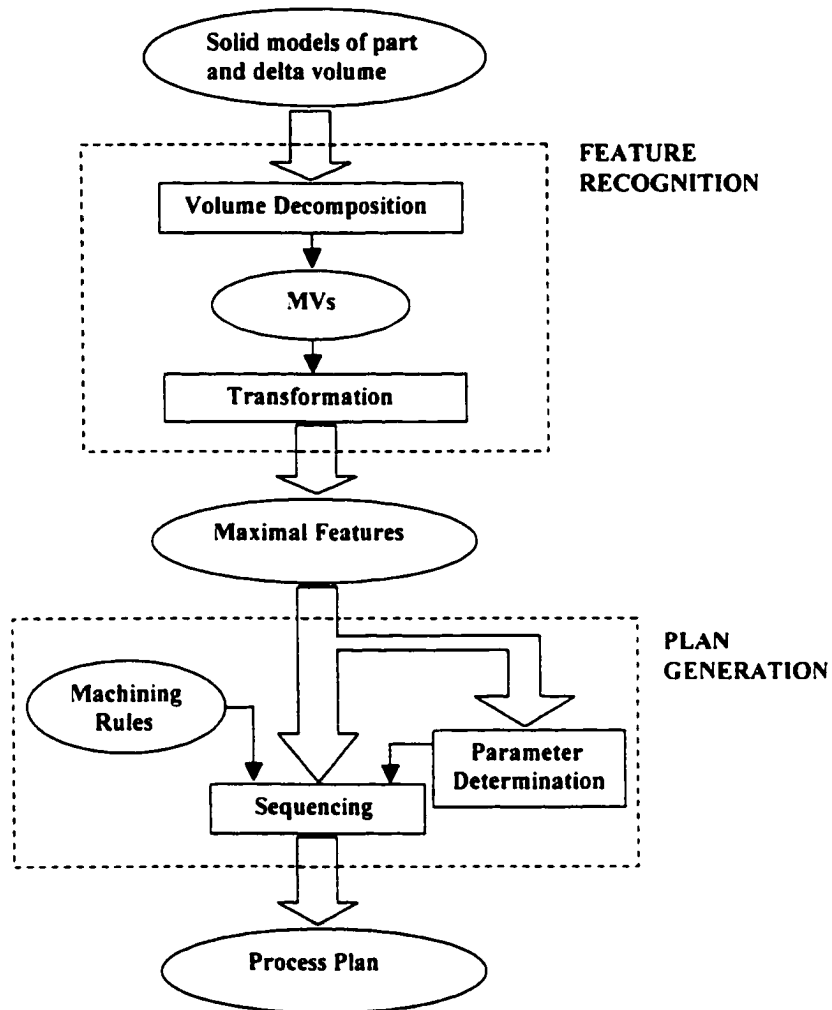


Figure 1.1 Optimal process plan generation.

1.5 Dissertation Organization

This dissertation consists of 7 chapters. In chapter 2, previous work related to this research is reviewed. Chapter 3 presents the definition of maximal feature and the algorithm to recognize maximal features from the solid models of the machined part and

its raw material. In chapter 4, the method for extracting and determining the machining parameters is presented. Chapter 5 presents the method to generate the optimal process plan using maximal features. Chapter 6 presents implementation and case studies. Finally, conclusions and research issues for future work are presented in chapter 7.

Chapter 2

Previous Work

2.1 Overview

In this chapter, the previous work related to this research is reviewed. Work on computer-aided process planning (CAPP) is first reviewed, and then work on feature recognition and other related work are reviewed.

2.2 Computer-Aided Process Planning

Process planning is a task to set a plan needed to manufacture products from designs. Process planning includes a family of planning subtasks such as selection and sequencing of manufacturing operations, determination of process parameters, and selection of cutting tools. In general, process planning is a complex task that requires thorough understanding of both the design requirements of the part and of the available manufacturing processes and their capabilities.

The manufacturing of parts, particularly by machining, has generated the need for the development of new computer-based planning automation. The development of comprehensive geometric modeling of mechanical parts was followed by the development of computer-aided manufacturing systems that automate the generation of NC programs. It was quickly realized that the planning of machining processes included

considerably more than generating the tool path and a substantial amount of research work was carried out in computer-aided process planning (CAPP). In pursuing CAPP, there have been mainly two approaches: variant and generative.

2.2.1 Variant Process Planning

Earlier attempts for computer-aided process planning consisted primarily of building computer-assisted systems, where human planners made the decisions. These systems, called variant process planning, use group technology to retrieve the process plan for a part from the database of similar parts. The human process planner then modifies the process plan manually to produce a customized plan for the part. Examples include CAPP [20] and MULTIPLAN [28].

The variant process planning is flexible and has low investment costs [48]. However, this approach becomes inefficient and unmanageable when the number of process plans and revisions to those plans increases. Consequently, inconsistent plans and large time requirements for planning often result. Furthermore, variant process planning relies on expertise and preferences of human process planners. The expertise and preferences are the key factors in determining the quality of the resulting plans. In effect, the computer is just a tool to assist in manual process planning, and automation of process planning was by no means achieved.

2.2.2 Generative Process Planning

Research efforts have been made to achieve automated process planning. Many researchers attempted to develop generative process planners that generate process plans

for parts automatically using the feature-based models* of the parts. Unlike the variant approach, the generative approach does not require the assistance from the user to generate a process plan. But presently there is no generative process planner that can generate process plans good enough for practical use.

Rule-based process planning was a common approach to generative process planners. These systems, often referred to as expert systems, attempted to generate plans based on database of machining related rules. Examples of systems that use this approach include GARI [7], TOM [25], and PROPLAN [27]. However, rule-based systems suffer from two major drawbacks: fragility and inefficiency [39]. The problems associated with rule-intensive techniques have spurred more interest in algorithm-based approaches. However, it is noted that since some degree of domain knowledge is always necessary for planning real-world planning, algorithmic systems do depend to an extent on rules. In that sense, almost every algorithm-based system is a hybrid of rule-based and algorithm-based methods [39].

Chang [17] proposed a process planning system called QTC. They identified interactions among features such as physical intersections, cutter accessibility, etc., and then used the interactions in selecting setups and sequencing the machining features with employing various machining rules and knowledge. A process planning system called NEXTCUT was proposed by Kambhampati et al [16]. Their system generated machining sequence for a machined part by performing planning and analysis step-by-step as a designer constructed or modified a design. QTC and NEXTCUT, however, relied on machining features defined by users with feature-based design. Gupta [9] worked on

* A feature-based model is a representation of the part as a collection of machining features such as holes, slots, and pockets.

automatic evaluation of manufacturability of a machined part. His method evaluated the plan to determine the manufacturability of the plan. In generating plans, he used a set of machining features called primary features [30]. Since a large number of alternative plans can be generated from the features, he reduced the number of alternative plans by pruning unpromising plans with various rules. Hayes [12] considered squaring constraints in developing a planning system. Her system created a feature plan by generating one or more possible operations for each feature and finding interactions among operations. Next her system selected a squaring plan, which is a partially ordered set of steps to cut the raw material into an accurate rectangular shape. Then the two plans were merged to produce the final process plan. The plan, however, needs to be verified by a human because there may be some interactions between steps that the interaction identification rules may be overlooked. Sakurai [36] proposed another method to automatically generate a process plan for a machined part. His method first recognizes machining features by decomposing the delta volume of the part. Here the delta volume is the difference between the raw material and the part. Since the features intersect each other, sequencing them in different orders can generate different plans. He then applied several machining heuristics to generating a good machining sequence. Yet optimization of machining sequence was not attempted.

Research in the area of computer-aided process planning varies in terms of application domain and the approach taken regarding the use of computational and modeling techniques. Although a considerable advancement has been achieved in computer-aided process planning, there does not exist a completely automated process planning system that can handle even moderately complex real-world parts. In order to

develop a process planning system that can generate process plans good enough for practical use, more research efforts need to be made to address the following issues:

1) Feature recognition

Existing systems for computer-aided process planning assume the feature-based models of parts. There have been attempts to generate feature-based models of parts by designing with features. However, due to the difference between design features and manufacturing features, there appears to be a general consensus that feature recognition is indispensable for computer-aided process planning.

2) Automatic fixture design

Automatic fixture design is an important but still a major missing component in computer-aided process planning. Automatic fixture design is extremely difficult since it requires not only detailed fixture configuration but also incorporation of other studies such as force and moment equilibrium and workpiece deformation. It is expected that human intervention is indispensable for a long time in future.

2.3 Feature Recognition for Machining

The need for critical information required for process planning goes beyond the shape of the part. However, the solid model of a design contains only geometric and topological information of the part. Consequently, most of previous work on computer-aided process planning rely on feature-based models of parts. With feature-based models, the information necessary for automated process planning can be obtained.

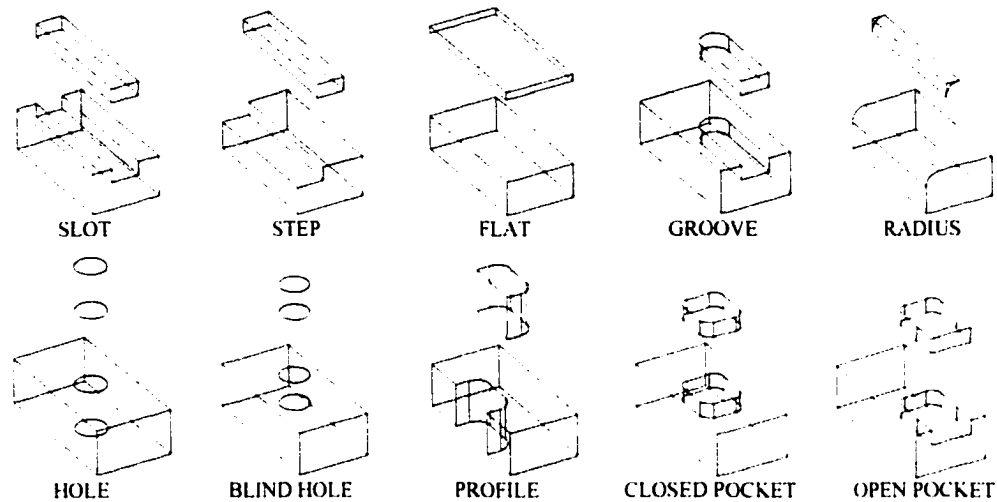


Figure 2.1 Examples of machining features.

Despite of the wide use of the term “features”, however, there has been no universally accepted definition of features [14]. One reason for this is that features are domain dependent and application-oriented. For different applications such as design, manufacturing and inspection, a part is to be viewed in terms of different sets of features. In the domain of machining, a feature can be viewed as a volume whose geometry and topology corresponds to a machining operation. Examples of the machining features are shown in Figure 2.1.

In creating a feature-based model, there are mainly two methods: feature recognition and feature-based design. Though each of the methods has advantages and disadvantages over the other, feature-based design is inferior to feature-recognition for the following reasons. First, the features used in design are different from the features used in manufacturing. There were efforts to map design features into manufacturing features, but design features that can be mapped to manufacturing features were limited.

Second, features are user-dependent. Even if designers use machining features, different designers can use different machining features in designing the same part. Moreover, designers need to acquire knowledge on manufacturing so that they use good machining features from which a promising plan can be generated. Accordingly, there appears to be a consensus that feature recognition is essential for feature-based modeling for automated process planning. In the following sub-sections, work on feature recognition for machining is reviewed.

2.3.1 Graph-Based Feature Recognition

Research on feature recognition has been made for a long time. Earlier methods for feature recognition attempted to recognize a feature in the B-rep of a solid model by finding the topological and geometric pattern unique to the feature. These patterns are represented by graphs whose nodes denote faces, and an arc connecting two nodes denotes adjacency of the two faces of the nodes.

In graph-based feature recognition, machining features are recognized by searching the patterns in the data structure of a solid model. Figure 2.2(a) shows an example of graph pattern that corresponds to a slot feature. These methods [6,13,15,33] can recognize isolated features quickly, but they have difficulty in recognizing intersecting features since the topological and geometric patterns of the features are destroyed by the intersection. An example of the destroyed pattern is shown in Figure 2.2(b). Accordingly, recognition of intersecting features had been an issue in feature recognition.

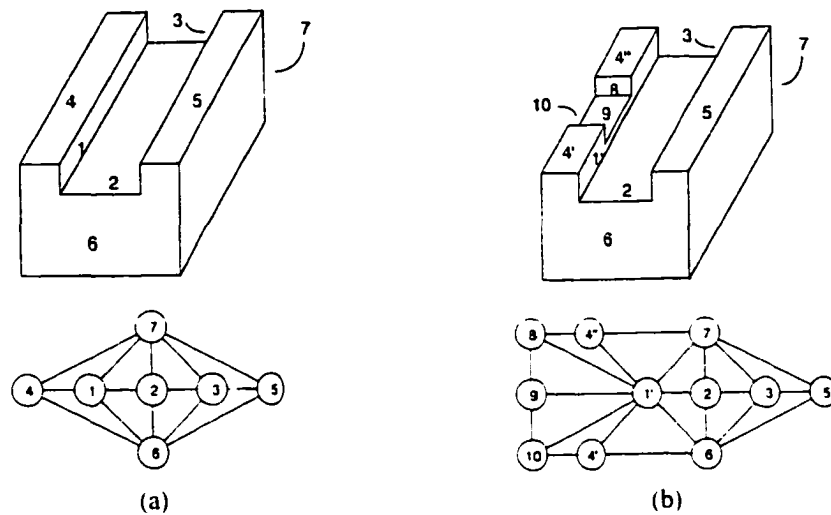


Figure 2.2 Graph matching method: (a) typical graph pattern for slot feature; (b) the pattern is destroyed by intersecting feature. (from [40]).

2.3.2 Hint-Based Feature Recognition

Recently several methods that can recognize intersecting features have been developed. The methods grouped in the name of hint-based feature recognition [8,10,31,32,44] search feature hints, which are topological and geometric patterns that suggest the possibilities of the existence of features. They generate volumes corresponding to features suggested by the hints and verify the existence of the features using the volumes. For example, cylindrical or conical faces in a solid model are hints of drilling features and planar faces are hints of milling features. Since a face created by the end of an end-mill cutter is planar and perpendicular to the wall faces created by the side of the cutter, the volume of a possible milling feature hinted by a planar face is generated by sweeping the planar face in the direction normal to the face. Then this candidate volume is examined for cutter accessibility, interference with the part etc. to see if it is

really a feature. In general, the use of other types of hints such as design feature information and tolerance information has been suggested, but their actual use seems very limited.

Regli [30] proposed a hind-based method to recognize machining features called primary features. Primary features of a part are machining features whose volume is not contained by that of any other machining feature. However, since an edge of a primary feature is not necessarily convex[†], it may be geometrically complex and may result in less efficient machining operation. Because of the extensive use of solid modeling operations, his method is not efficient enough for real industrial parts. Thus, he proposed to use multiple processors for feature recognition to improve the scalability [32]. An example of primary feature is shown in Figure 2.3(c).

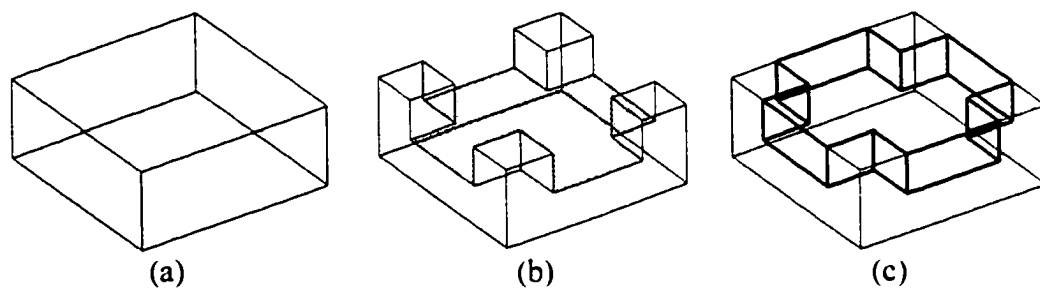


Figure 2.3 Primary feature: (a) raw material; (b) part, (the grayed face is the hint of a milling feature); (c) primary feature.

Han [10] also proposed a hind-based method. Since his method can generate multiple feature interpretations, he used certainty factor to determine the promising features. However, the assignment of the certainty factors is rather arbitrary, and the

[†] A convex edge of an object is an edge that has the solid angle equal to or less than 180° at any point on it when the object is cut the plane normal to the edge at that point.

method did not consider more important factors such as setups, and global relationships among features.

2.3.3 Feature Recognition by Volume Decomposition

Feature recognition by volume decomposition [19,36,37,38,41,47] has been another trend. Kim [19,47] developed a convex-hull-based volume decomposition method called alternating sum of volumes with partitioning (ASVP), which decomposes a solid into form features by recursively generating the convex hull of an object and subtracting the object from the convex hull. Figure 2.4 shows the process of the method with an example part. The algorithm of the ASVP is relatively fast. However, it cannot deal with curved objects since generating the convex hull for a curved object is often extremely difficult.

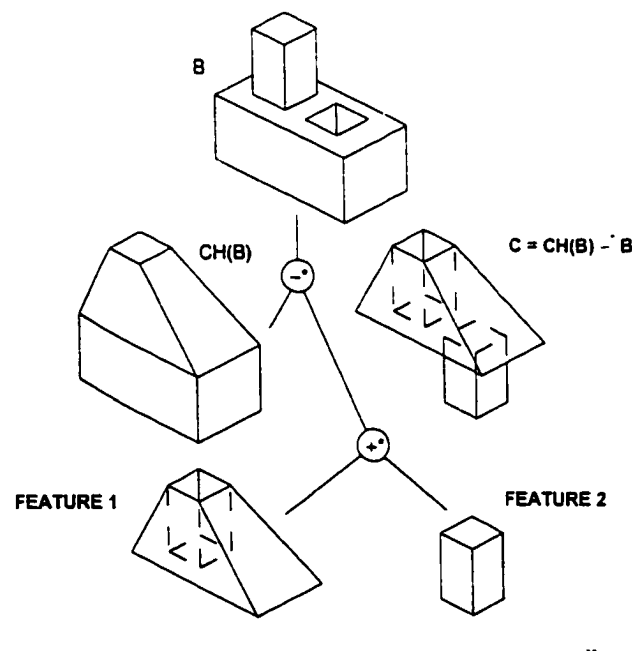


Figure 2.4 Alternative sum of volumes with partitioning (from [40]): $CH(B)$ denotes the convex hull of object B .

Some researchers developed cell-based volume decomposition methods that decompose a delta volume into volumes of simple shapes and then match the volumes for machining features [36,37,38,41]. Shah et al. [41] developed a method that decomposes a delta volume into minimum convex cells by intersecting halfspaces of the delta volume and their complements with the delta volume in different orders, and then composing these cells into maximum convex cells. However, due to the B-rep to CSG conversion problem [42], their method has a difficulty in decomposing curved objects into maximum convex cells.

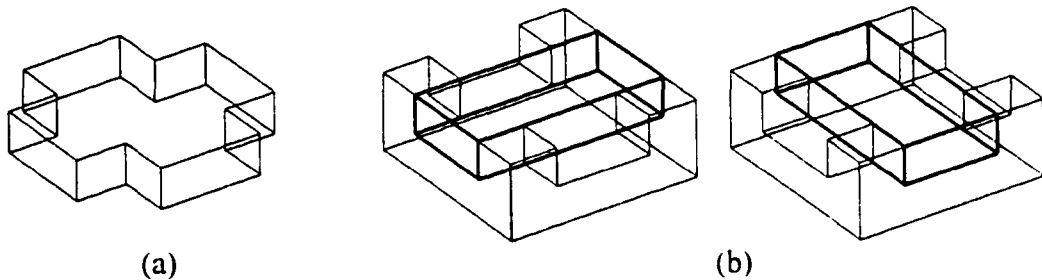


Figure 2.5 Maximal volumes: (a) the delta volume of the part in Figure 2.3(b); (b) two maximal volumes of the delta volume.

Sakurai et al. [36,37] developed the concept of maximal volumes and the method to generate them. A maximal volume of an object is a volume that is a subset of the object, that has as few concave edges as possible, and that is not contained by any other such volume. Examples of maximal volumes are shown in Figure 2.5. In generating maximal volumes, they first generated minimal cells and then composed them into maximal volumes. Though the combinatorial complexity was decreased by composing only a certain kinds of minimal cells that lead to maximal volumes, the method was still

computationally expensive. They applied the concept to feature recognition for machining by decomposing the delta volume of a part into maximal volumes.

Since methods based on volume decomposition consider only nominal geometry of a part in recognizing features, they may result in some volumes that are not suitable as machining features.

2.3.4 Research Issues in Feature Recognition

To develop a feature recognition method that can be used in a practical application, the following issues need to be addressed:

1) Which features to recognize

When features intersect, it is possible to recognize multiple sets of machining features, and each of the sets can be used in generating process plans for the part.

This poses a problem of which set of machining features should be recognized.

We think that a set of machining features that optimizes a certain objective function such as machining time should be recognized.

2) Scalability

Another issue in feature recognition is scalability [11]. The existing methods capable of recognizing intersecting features are slow, so it sometimes takes unacceptably long for them to recognize machining features for complex parts. For practical applications with complex industrial parts, the scalability needs to be improved.

2.4 Other Related Work

In performing computer-aided process planning, it is crucial to optimize machining parameters that affect the quality of plans. These machining parameters include cutter sizes, setup directions, feed rates, cutting speed, depth of cut and etc. Among them, setup directions and cutter sizes are two important factors in process planning, and there were research efforts on these areas.

Chu et al. [4] proposed a feature-based approach for setup minimization. In their method, features are classified according to the number of possible tool approach directions in which they can be machined. They minimized the total number of setups for machining a part by grouping every feature having single tool approach direction and by choosing the appropriate tool approach direction for each feature having multiple tool approach directions. There sometimes exist cases where there are more than one set of minimum setups for a part, but they did not consider such cases.

Bala et al. [2] developed a method to automatically select cutters for pocket features. They proposed to use a combination of two cutters for machining a pocket. They selected the smaller cutter size so that it is equal to the smallest pocket corner radius. The larger cutter size was then selected such that the unmachined area that remains after its use can be removed by moving the smaller cutter along the pocket contour. Though selection of the largest cutter for a pocket requires consideration of other features intersecting the pocket, their method considers only the geometry of the pocket to be machined.

Veerami et al. [46] proposed to select an optimal set of cutter sizes for machining a prismatic pocket with a given set of cutters. Their approach did not limit the number of

cutters to be selected. They generated cutter path by generating volumes called Voronoi mountains and then slicing it at different depths, and estimated machining time for each cutter of the given set. Then they used a dynamic programming to select a set of cutters which results in the least processing time. They dealt with pockets with only planar faces, and it is presumed that the method has a difficulty in generating the Voronoi mountains for pockets having curved faces.

Chapter 3

Recognition of Machining Features

3.1 Machining Feature to Be Recognized

Machining is a manufacturing method to create a part by cutting off a certain portion of the raw material. Creating a part by machining usually requires a set of machining operations such as drilling and pocket milling. In general, machining operations for a part are selected based on the part geometry, design specifications, and manufacturing capability of the machine shop. In this research, a machining feature is defined as a volume that can be removed by one machining operation. Here one machining operation means a movement of one cutter in one setup without retracting the cutter from the workpiece. Examples of machining features include hole, slot, step, pocket, and etc.

Machining features that can be recognized in a part are not unique. There are often various sets of machining features^{*}, each of which can create the same part. For example, the part in Figure 3.1 can be created by machining any one of the sets {FTR1}, {FTR2, FTR3}, and {FTR4, FTR5, FTR6}. Selecting a set of the features can greatly affect the quality of process plan. This non-uniqueness of machining features to be recognized poses a problem of which set of machining features should be recognized.

^{*} A set of machining features is also called a feature interpretation.

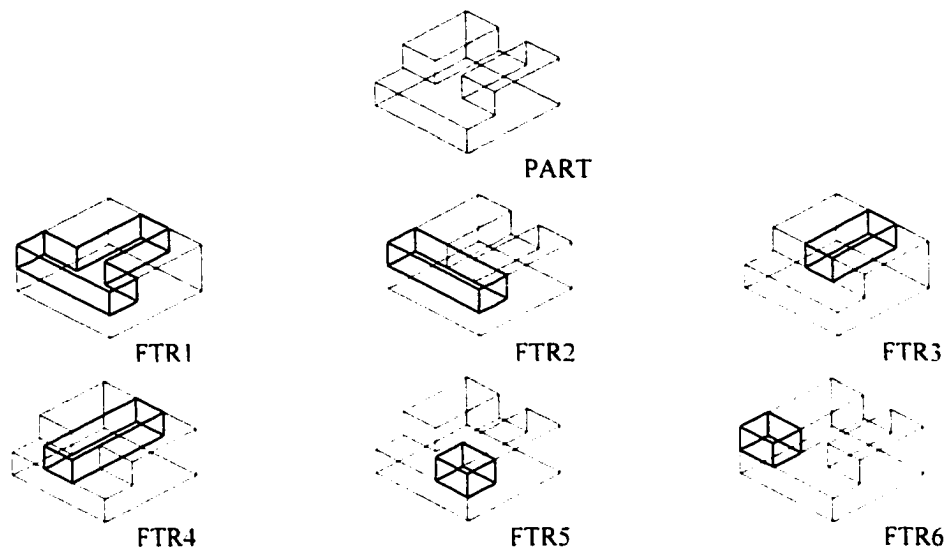


Figure 3.1 A machined part and its machining features.

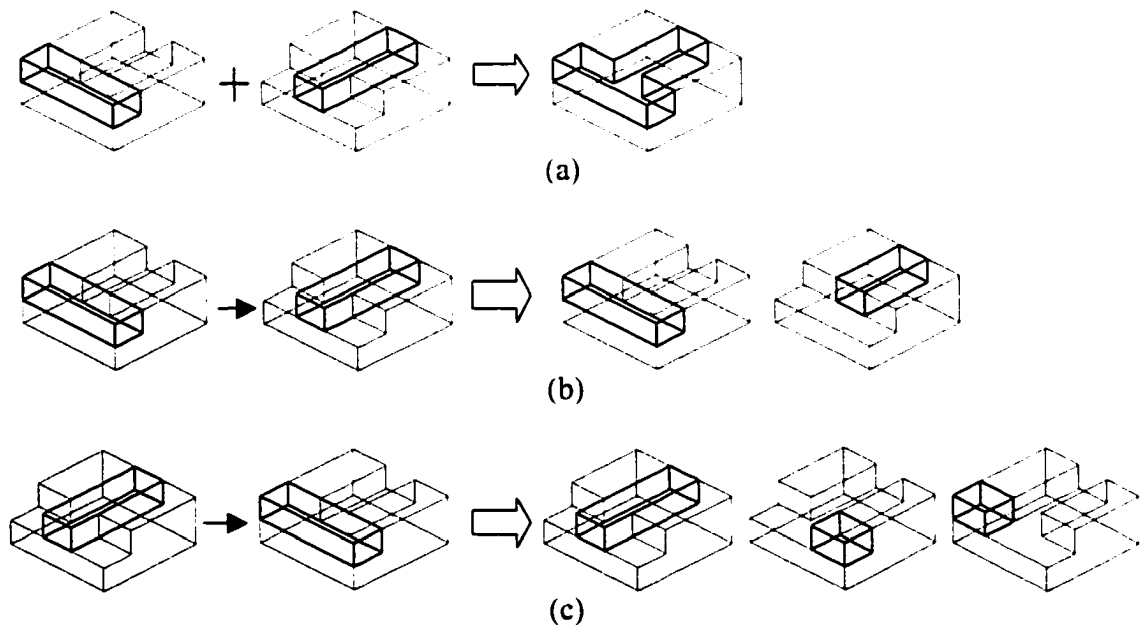


Figure 3.2 (a) Merging FTR2 and FTR4 results in FTR1; (b) machining FTR2 first and then FTR4 results in FTR2 and FTR3; (c) machining FTR4 first and then FTR2 results in FTR4, FTR5, and FTR6.

In this research, we want to recognize the set of machining features that requires the shortest machining time. To do this, first we recognize a set of the machining features, called maximal features (MFs), from which different sets of features can be generated. For example, FTR2 and FTR4 in Figure 3.1 are recognized as maximal features. Then three different sets of machining features {FTR1}, {FTR2, FTR3}, and {FTR4, FTR5, FTR6} can be generated from the two features as shown in Figure 3.2. The optimal set of machining features will be generated by actually performing process planning with the maximal features later.

3.2 Recognition of Maximal Features

3.2.1 Definition of Maximal Feature

We propose to recognize a set of large and simple machining features, called maximal features (MFs), from which different feature interpretations can be generated. In general, a maximal feature satisfies the following conditions:

- (1) The volume of the maximal feature is a subset of the delta volume.
- (2) The maximal feature has no concave edges[†].
- (3) A halfspace[‡] of the maximal feature is a halfspace of the delta volume.
- (4) The maximal feature is not contained by any other feature satisfying the above three conditions.

[†] A concave edge of an object is an edge that has the solid angle greater than 180° at any point on it when the object is cut with the plane normal to the edge at that point.

[‡] A halfspace is usually unbounded geometric entity that divides the Euclidean space into two infinite portions. A surface can be considered as a halfspace boundary and a halfspace can be considered as a directed surface. Formally, a halfspace is defined as a regular point set in E^3 : $H = \{P: P \in E^3 \text{ and } f(P) < 0\}$ where P is a point in E^3 and $f(P) = 0$ defines the surface equation of the halfspace boundary.

It is obvious that a feature to be recognized needs to satisfy the first condition. Usually, machining a part with simple straight cutter paths is more efficient than machining the part with non-straight cutter paths. For example, in creating the part in Figure 3-3(a), it is more efficient to machine the three slots shown in Figure 3-3(c) than the open pocket in Figure 3-3(b) since larger cutters can be used in machining two of the three slots. Subsequently, it is easier to construct cutter paths for the slots than that for the open pocket, which is evidenced by efforts to divide concave pocket areas into convex ones for cutter path construction [24]. This is the reason for the second condition. With the third and fourth conditions, we recognize large features whose faces are in area contact with the part so that different feature interpretations can be generated. Though

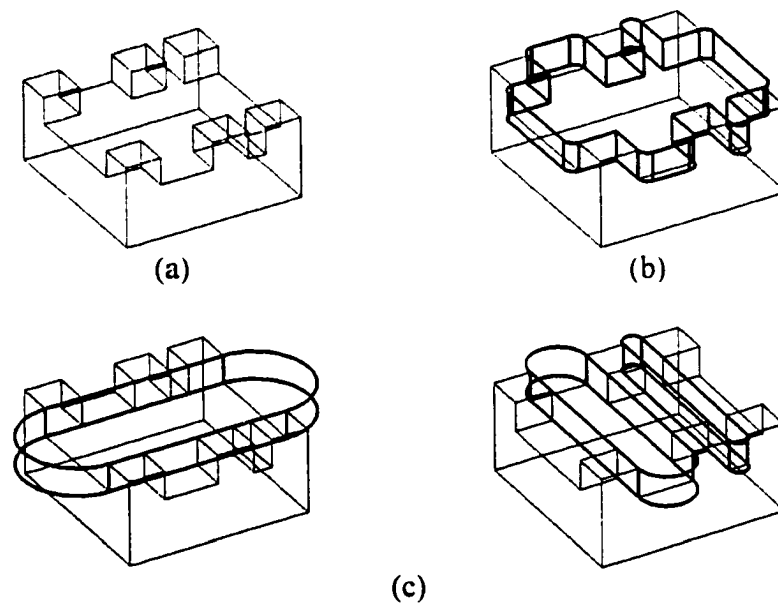


Figure 3.3 Which features are better? Cylindrical faces are intended to denote cutter sizes: (a) part; (b) one pocket feature; (c) two slot features.

most maximal features of parts satisfy the conditions in the previous page, there are exceptions explained later in sections 3.3 and 3.4.2.

Figure 3.4 shows examples of maximal features. FTR1 and FTR2 in Figure 3.4 are maximal features of the part. FTR3 is not a maximal feature because it is contained by FTR1. FTR4 is not a maximal feature either, because it has concave edges.

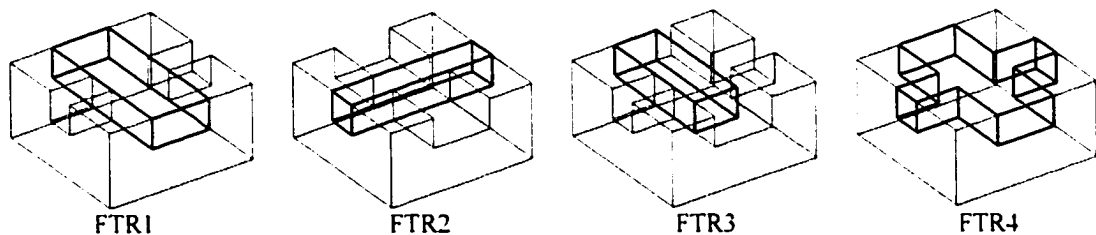


Figure 3.4 Examples of maximal features: FTR1 and FTR2 are maximal features of the part.

3.2.2 Process of Recognition of Maximal Features

The basic idea underlying in recognition of maximal features in this research is to decompose the delta volume into volumes so that the volumes correspond to maximal features. To do so, we first attempt to decompose the delta volume into large and simple volumes called maximal volumes (MVs), which is explained in the next section, and then transform them into maximal features. Figure 3.5 shows the process of maximal feature recognition. The process consists of three steps: volume decomposition, selection, and conversion.

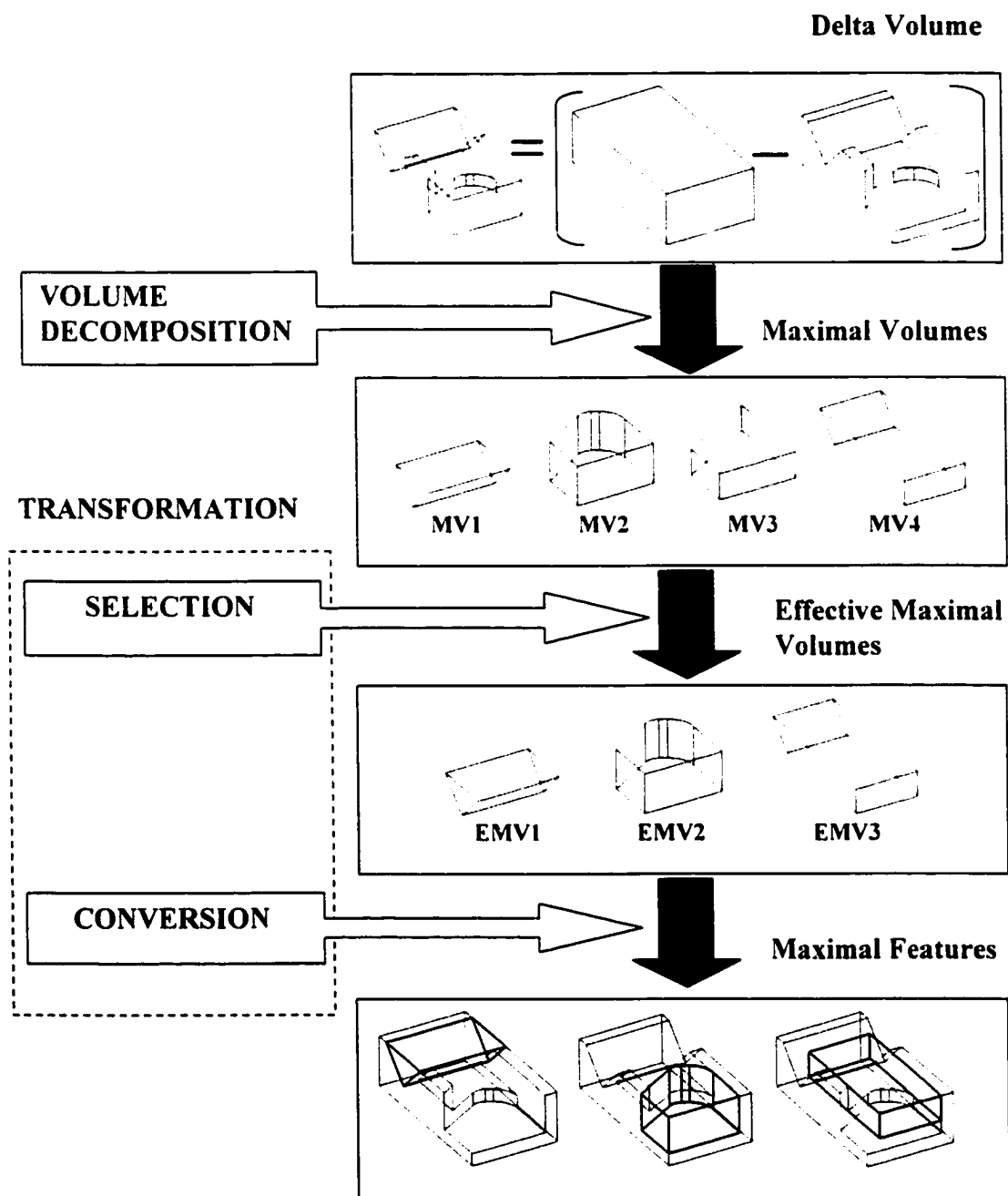


Figure 3.5 Process of maximal feature recognition.

(1) Volume decomposition

In this step, the delta volume generated by subtracting the part from the raw material is decomposed into its maximal volumes. For example, the delta volume in Figure 3.5 is decomposed into four maximal volumes.

(2) Selection

If all the part faces created by subtracting a maximal volume from the raw material can be also created by removing other maximal volumes, then the maximal volume is redundant. In this step, only non-redundant maximal volumes, called effective maximal volumes, are selected. For example, MV3 in Figure 3.5 is redundant since all the part faces created by subtracting it from the raw material can be created by removing MV2 and MV4. Thus, MV1, MV2, and MV4 are selected as effective maximal volumes. The union of effective maximal volumes is the delta volume.

(3) Conversion

As defined before, a feature needs to be machined in a single machining operation with a 3-axis machine. In this step, each of the effective maximal volumes is examined if it is a feature that can be machined in a single machining operation. If so, it is recognized as a maximal feature. Otherwise, it is converted into maximal feature(s) by further decomposing it. For example, EMV3 in Figure 3.5 is unmachinable in a single setup because the slanted face is neither parallel nor perpendicular to other faces in area contact with the part. Thus, it is converted into a maximal feature.

3.3 Maximal Volume Decomposition

The first step of maximal feature recognition is to decompose the delta volume into volumes called maximal volumes. Our initial effort for volume decomposition was to decompose a delta volume into maximal convex volumes whose halfspaces are the halfspaces of the delta volume. For delta volumes having curved faces, however, it is sometimes impossible to decompose them into such volumes.

Figure 3.6 shows an example. The delta volume in Figure 3.6(a) has a concave edge. To decompose this delta volume into volumes having no concave edges, it is necessary to introduce new halfspaces, and the complements of the cylindrical halfspaces are the easiest choice as new halfspaces. The delta volume in Figure 3.6(a) can be decomposed into three volumes having no concave edges with the complement halfspaces. However, the introduction of these new halfspaces is not desirable since it

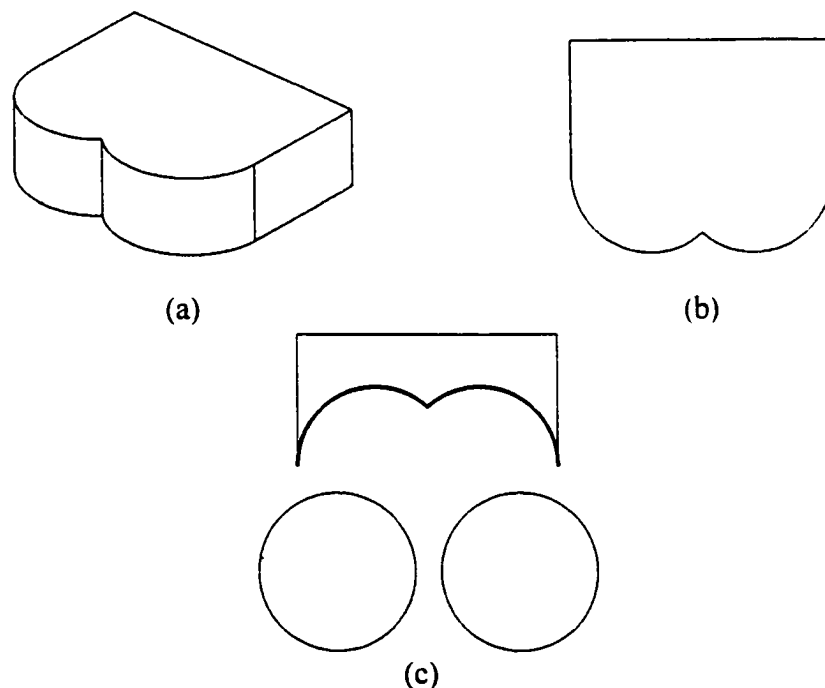


Figure 3.6 (a) object; (b) top view; (c) maximal convex-edged volumes.

would be more efficient to create the part by machining the delta volume as a single machining feature. Creating the part by machining the three volumes in Figure 3.6(c) is awkward and impractical. Therefore, we want to decompose a delta volume into volumes in such a way that the volumes have only the halfspaces of the delta volume and that each of the volumes has as few concave edges as possible. These volumes are called maximal volumes.

Formally, a volume V is a maximal volume (MV) of a delta volume Δ if V satisfies the following conditions:

- (1) $V \subseteq \Delta$,
- (2) each of the halfspaces of V is a halfspace of Δ ,
- (3) V has as few concave edges as possible,
- (4) for each face of V , there exists a face of Δ such that the intersection of the faces is a two manifold with boundary, and
- (5) $V \not\subset A$, where A is a volume that satisfies the above conditions.

As explained in section 3.2.2, maximal features are recognized using maximal volumes of the delta volume. Therefore, if there are maximal volumes having concave edges, there will be also maximal features having concave edges. This is an exception to the properties of maximal features presented in section 3.2.1.

3.3.1 Previous Method for Maximal Volume Decomposition

Sakurai et al. [38] developed a method to decompose a delta volume into maximal volumes. The method consists of two steps: decomposing the delta volume into minimal cells and merging the cells into maximal volumes. Figure 3.7 shows the process of the maximal volume decomposition.

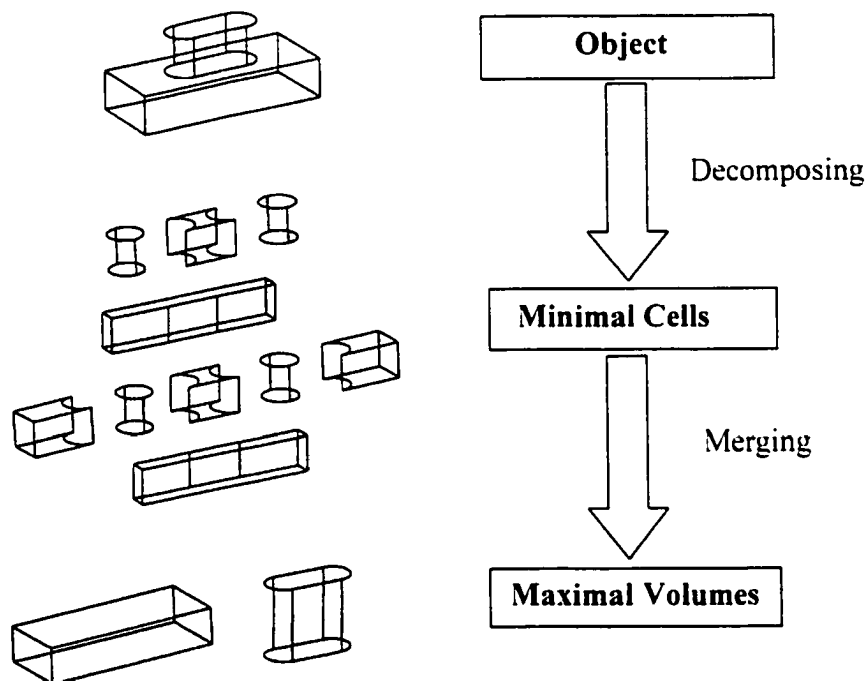


Figure 3.7 Maximal volume decomposition (from [38]).

(1) Decomposing the delta volume into minimal cells

First, the faces of the delta volume are extended and intersected with one another to generate edges. Then, faces are generated by connecting the edges. Next, minimal cells are constructed by connecting the faces.

(2) Merging the cell into maximal volumes

In this step, minimal cells are merged into volumes so that the volumes conform to the conditions for maximal volumes presented in section 3.3.

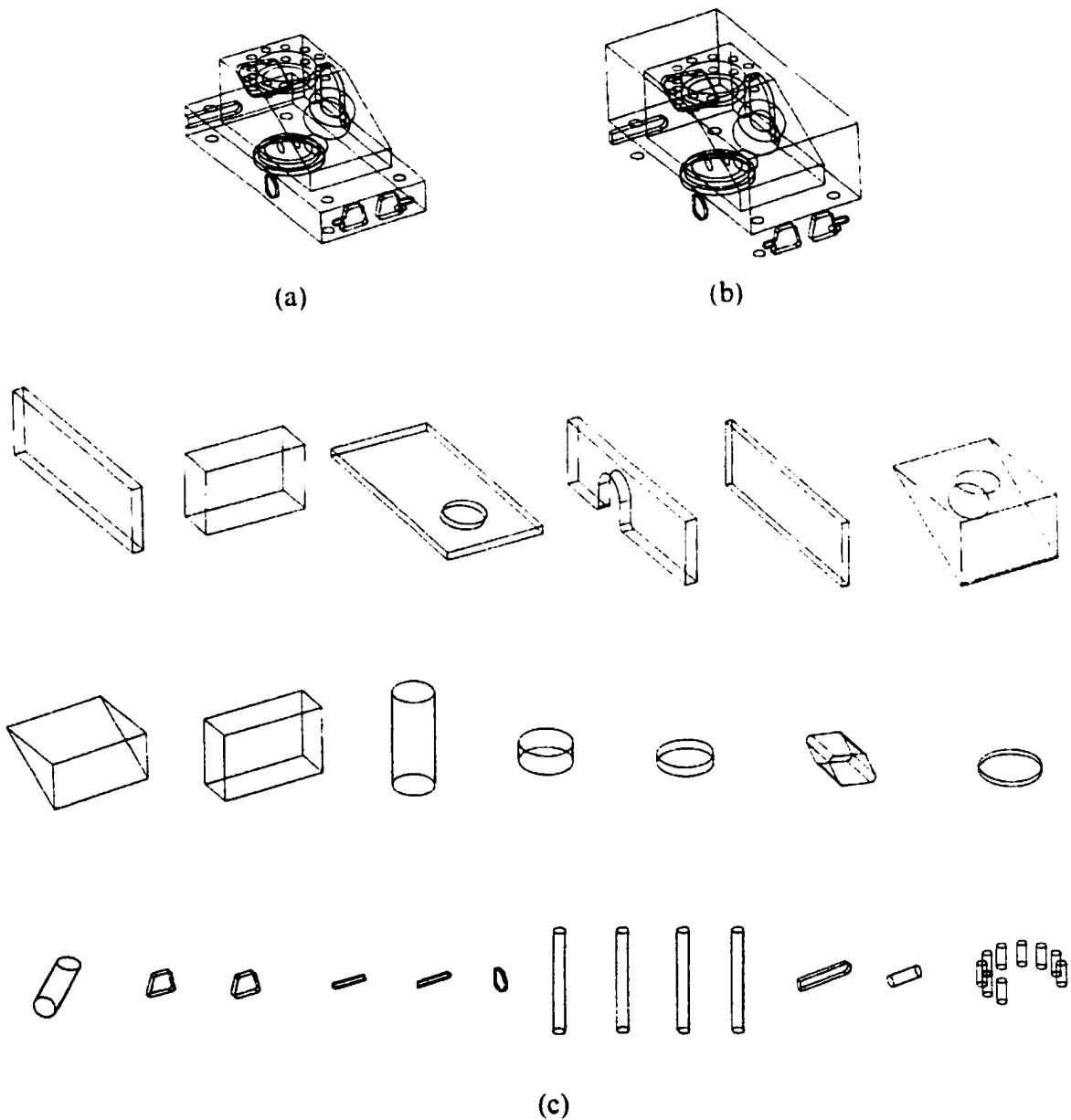


Figure 3.8 (a) ANC101 test part; (b) delta volume; (c) maximal volumes of the delta volume.

Figure 3.8 shows ANC101 test part, delta volume, and maximal volumes of the delta volume generated by the method. Most of the maximal volumes of the delta volume correspond to maximal features.

Note that each maximal volume is the combination of some minimal cells, and thus all maximal volumes can be found by generating and testing every combination of minimal cells. To ease the combinatorial complexity, the method in [38] starts with a cell and keeps adding adjacent cells. By doing so, many combinations can be pruned and the expensive generate-and test operation can be avoided.

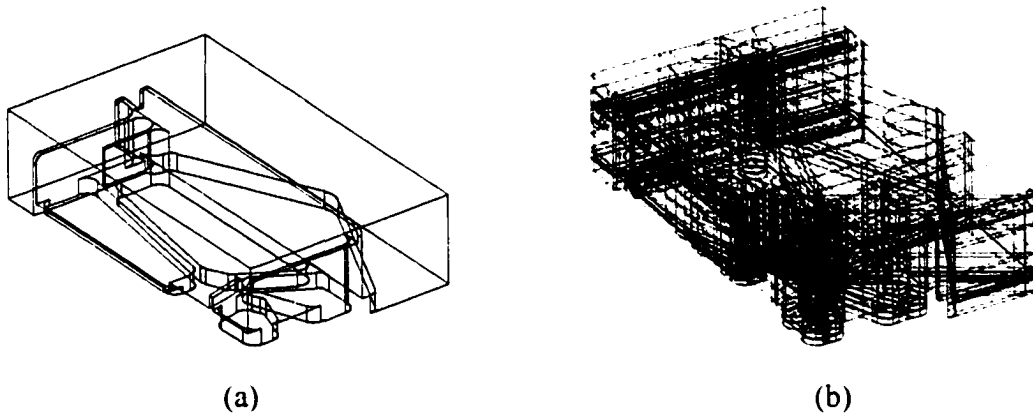


Figure 3.9 Combinatorial complexity due to the large number of minimal cells.

Though a large number of combinations are pruned by the method, yet the method suffers from the combinatorial explosion for a delta volume that is decomposed into a large number of minimal cells. For example, Figure 3.9(b) shows the minimal cells of the delta volume in Figure 3.9(a). As seen in the figure, the number of minimal cells of the delta volume is so large that the delta volume is not decomposed into maximal volumes within any practical length of time.

3.3.2 Recursive Maximal Volume Decomposition

To reduce the combinatorial complexity and generate maximal volumes fast, a recursive volume decomposition method has been developed in this research. The method is based on 'divide-and-conquer' paradigm and consists of the three steps:

- (1) Bisection
- (2) Decomposition
- (3) Composition

In the step of bisection, a delta volume is recursively bisected into volumes until the volumes have only small numbers of faces. Next, in the step of decomposition, each of the sub-volumes is decomposed into maximal volumes of the sub-volumes by the method presented in the previous section. These maximal volumes of the sub-volumes are then composed into the maximal volumes of the delta volume in the step of composition.

For example, the delta volume in Figure 3.10 is divided into four sub-volumes AA, AB, BA, and BB as shown in the third row. Each of these sub-volumes is then decomposed into its maximal volumes as shown in the fourth row. Then the maximal volumes of AA and AB are composed into the maximal volumes of A as shown in the fifth row of the figure. Likewise, the maximal volumes of BA and BB are composed into the maximal volumes of B. Next, the maximal volumes of A and B are composed into the maximal volumes of the delta volume as shown in the sixth row. In the followings, each of the steps is explained in more detail.

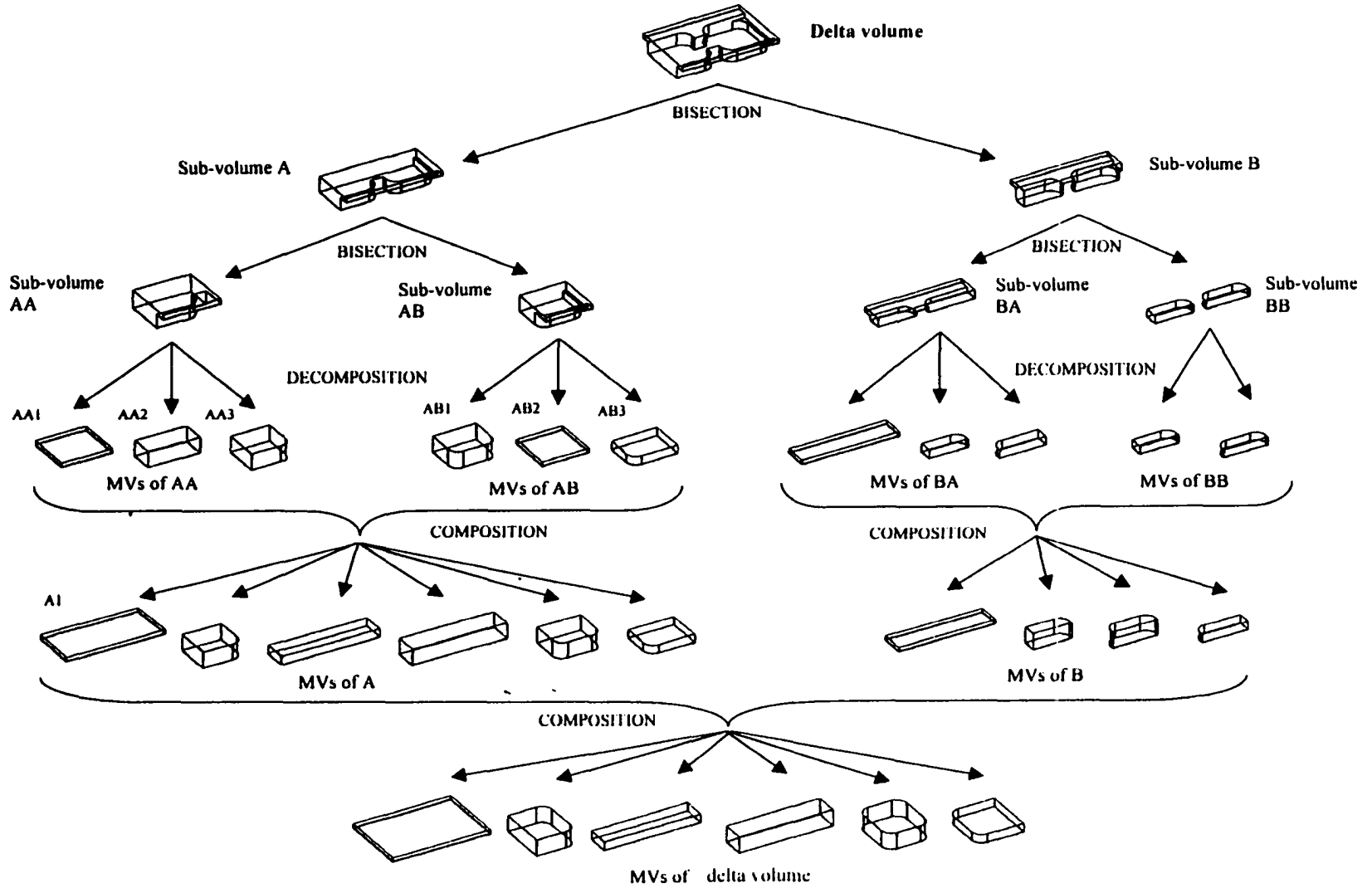


Figure 3.10 Recursive volume decomposition.

3.3.2.1 Bisection and Decomposition

A common approach in solving large or complex problems is 'divide-and-conquer'. Divide-and-conquer is an algorithmic technique with which the instance of a problem is divided into two or more smaller instances. Then a solution for each of these smaller instances is found, and the solutions are combined to produce a solution for the original instance. Typical examples include binary search and the Fast Fourier Transform (FFT). This divide-and-conquer approach is applied to maximal volume decomposition to speed up the decomposition.

In maximal volume decomposition, combinatorial complexity occurs when a solid is decomposed into a large number of minimal cells. The number of minimal cells depends on the number of faces and the number of concave edges of the delta volume. Thus, the idea of this step is to recursively bisect a delta volume into volumes so that the volumes have smaller numbers of faces and concave edges. Whether a volume should be bisected or not is judged by the number of faces of the solid. If the number of faces is bigger than a reference number, which is currently set to 15, the solid is bisected. For example, the delta volume in Figure 3.10 is bisected into volumes A and B, and they are bisected again into volumes AA, AB, BA and BB.

A bisecting plane is selected so that a solid is divided into volumes having a similar number of faces. If there is no such a plane, a plane that bisects the bounding box of the solid in the middle is selected. Once the delta volume is recursively bisected into simple volumes, maximal volume decomposition is applied to each of the volumes.

3.3.2.2 Composition

Hereafter V_{B1} and V_{B2} denote the two volumes created by bisecting a volume, and MVs of V_{B1} and V_{B2} are called child MVs. MVs of the bisected volume are called parent MVs. In Figure 3.10, for example, MVs of AA and MVs of AB are child MVs for A, and MVs of A are parent MVs for AA and AB. When a volume is bisected into two volumes by a plane, each of the two volumes has one or more faces created by the bisection. A child MV's face in area contact with the bisecting plane is denoted by F_B .

As seen in Figure 3.10, a child MV is not necessarily a parent MV. For this reason, a child MV of V_{B1} may need to be composed with child MVs of V_{B2} into parent MVs. Likewise, a child MV of V_{B2} may need to be composed with child MVs of V_{B1} into parent MVs.

The process of composition is as follows. Each MV of V_{B1} is examined whether it can be extended to parent MV. To do so, the MV is first checked if it has an F_B . If the MV does not have any F_B , the MV itself is the parent MV. Otherwise, V_{B2} 's MVs in area contact with the F_B are collected. For example, the child MV AA1 in Figure 3.10 has an F_B , thus it is not a parent MV. Therefore, the child MVs AB1, AB2, AB3 that are in area contact with the F_B are collected. It is noted that only some of the collected child MVs may be necessary for generating parent MVs. Therefore, each subset of the collected MVs, starting with a subset with the smallest number of MVs, is checked if the union of child MVs of the subset covers the F_B . If so, the child MVs of the subset are added to the child MV of V_{B1} , and then parent MVs are generated from the union. For example, AB2, which is a subset of {AB1, AB2, AB3}, covers the F_B of AA1. Thus, A1 is generated from the union of AA1 and AB2. If a subset contains the subsets that have been used

earlier in generating parent MVs, the subset is not considered in generating parent MVs. The same process applies to child MVs of V_{B2} . This process continues until MVs of the delta volume are generated from its sub-volumes. As the final step, volumes that are not maximal volumes of the delta volume are discarded.

3.3.2.3 Performance

For the original method [38], the worst-case complexity of merging minimal cells can be represented as $O(2^N)^{\S}$, where N is the number of minimal cells of a delta volume. Assuming that the minimal cells are evenly distributed to $m+1$ sub-volumes generated by m bisections, the worst-case complexity of merging minimal cells for the recursive method can be represented as $O((m+1)2^{N/(m+1)})$. Consequently, the complexity of merging minimal cells is considerably alleviated. Composition of child MVs into maximal volumes of the delta volume also affects the total complexity of the recursive method, but it seems that the complexity of child MV composition is less dominant.

Table 3.1 shows the comparison of the performances between the original and recursive method. The table indicates that the recursive method improves the speed for MV decomposition significantly.

	Geometry of delta volume			Decomposition (sec)	
	# of planar faces	# of cylindrical faces	# of concave edges	Recursive	non-recursive
Part in Figure 3.8	66	38	57	18	>1800
Part in Figure 3.11	77	41	94	142	>1800
Part in Figure 3.12	45	30	87	25	>1800

Table 3.1 Comparison of original and recursive volume decomposition. Tested on a SGI Indigo MIPS R10000.

[§] There are 2^N combinations that can be generated with N minimal cells. For example, if there are two minimal cells A and B , then four combinations $\{A\}$, $\{B\}$, $\{A,B\}$, and $\{\emptyset\}$ are possible.

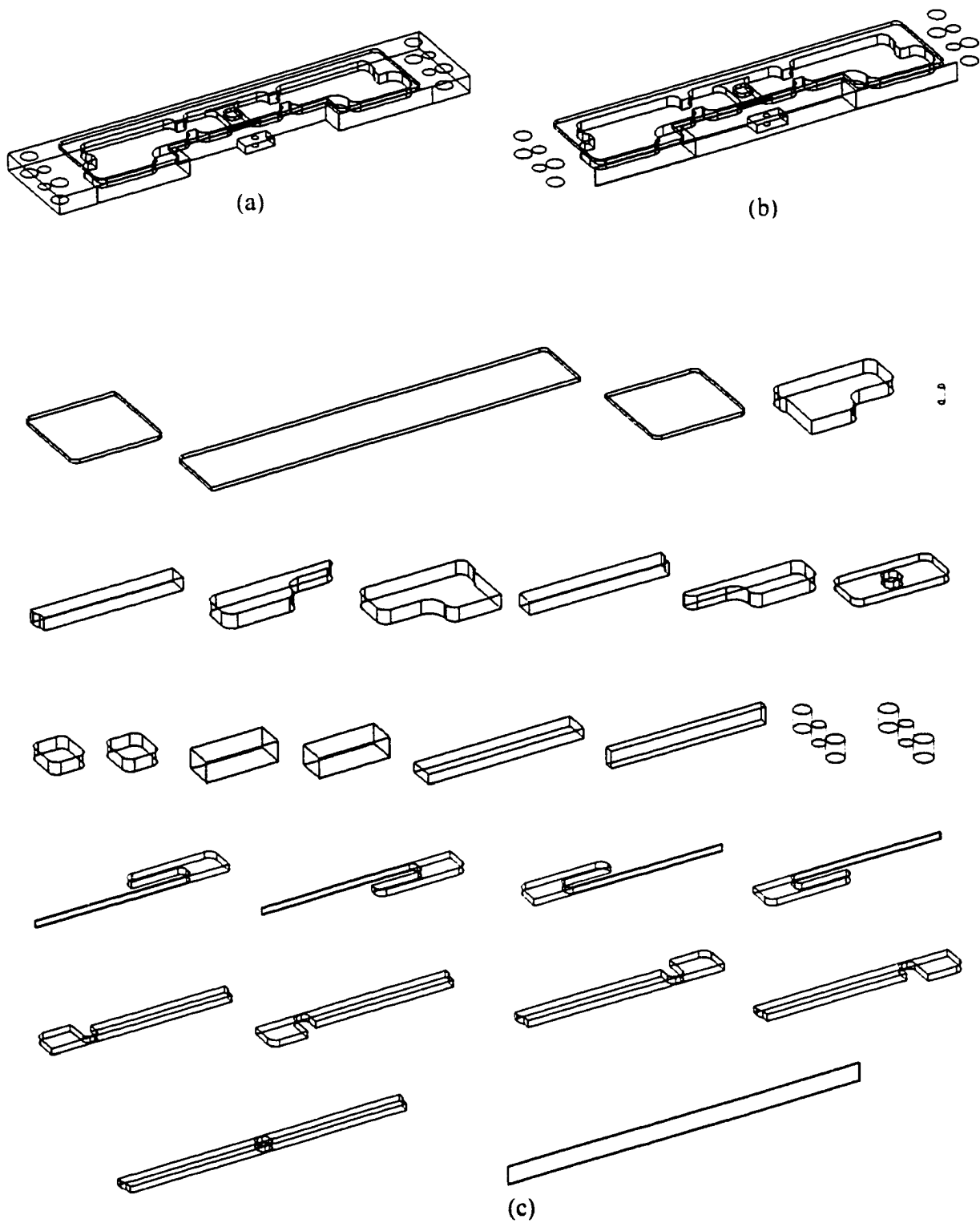


Figure 3.11 (a) part; (b) delta volume; (c) maximal volumes of the delta volume.

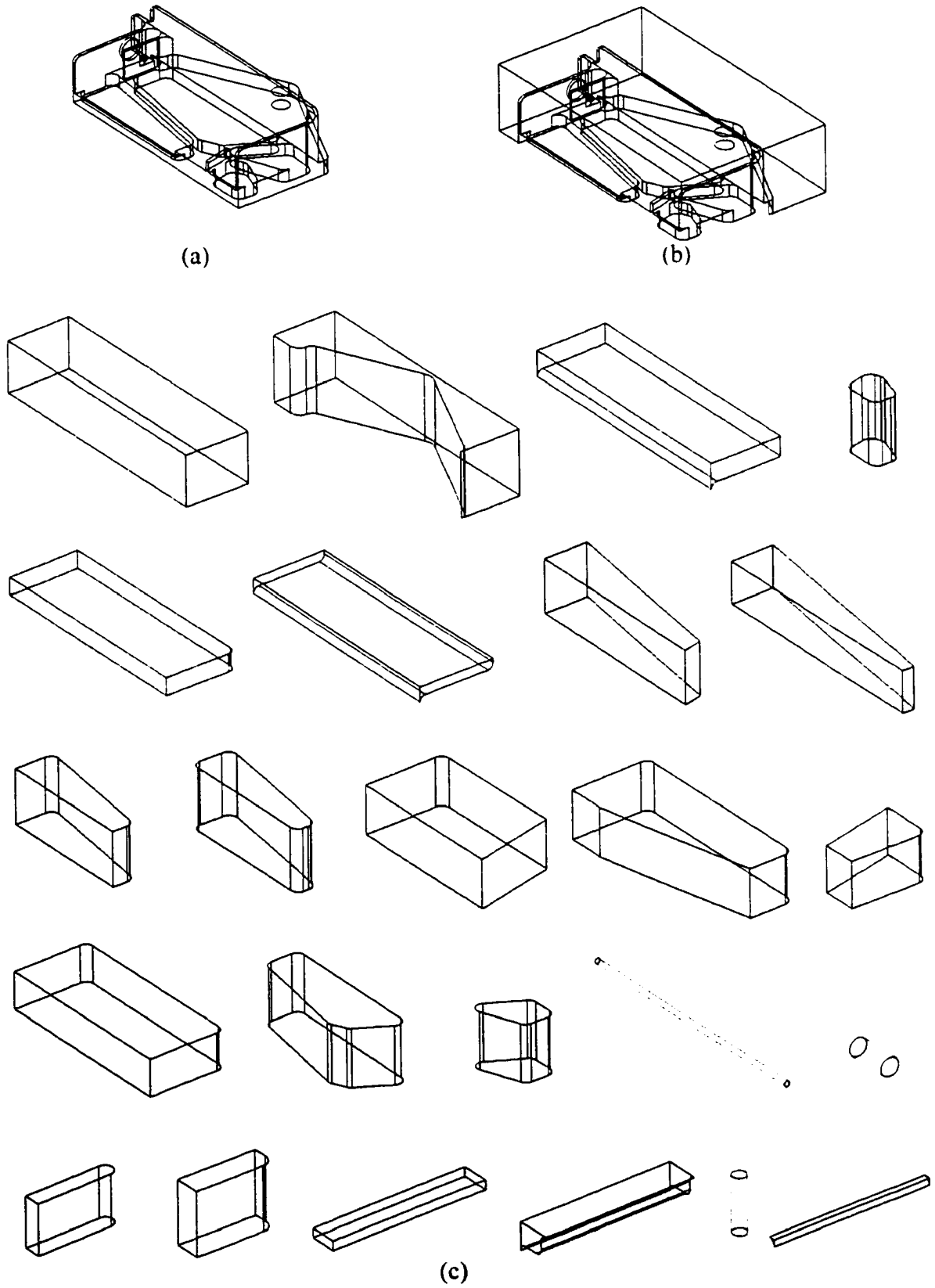


Figure 3.12 (a) part; (b) delta volume; (c) maximal volumes of the delta volume.

3.4 Transformation of Maximal Volumes into Maximal Features

Recognition of machining features requires consideration of not only geometry and topology of delta volumes but also the context of machining. Since only the geometry and topology of delta volumes are considered in generating maximal volumes, some maximal volumes may be redundant for machining and some maximal volumes may not be machining features. Such maximal volumes need to be transformed into maximal features in the context of machining. In the followings, the method to transform maximal volumes to maximal features is presented.

3.4.1 Selection of the Set of Non-Redundant Maximal Volumes

Some maximal volumes may be redundant in a sense that the part can be created by machining only some other maximal volumes of the delta volume. Thus, there is a need to select a set of non-redundant maximal volumes so that the same part face will not be machined more than once. For example, not all the maximal volumes in Figure 3.13(c) are necessary to create the part in Figure 3.13(a). Machining either {MV1, MV2, MV3} or {MV1, MV4} can create the part. Therefore, either of the two sets can be selected as a set of non-redundant maximal volumes for the part.

When a face of the delta volume is contained** only by an MV, the MV is called a *unique* MV. Table 3.2 shows the face containment of each of the MVs shown in Figure 3.13(c). The dot in the table indicates that the MV in the row contains the face in the

** If a face of MV completely covers a face of the delta volume, we say the MV *contains* the face of the delta volume.

column. For the delta volume shown in Figure 3.13(b), only MV1 and MV4 are the unique MVs. It is more desirable to select such unique MVs since it is better to machine a part face by a single machining operation. Thus, we select unique MVs as non-redundant MVs. If the union of all the unique MVs is the delta volume, the selecting process terminates, and the unique MVs are selected as the set of non-redundant MVs. For example, MV1 and MV4 are selected as the set of non-redundant MVs for the delta volume in Figure 3.13(b).

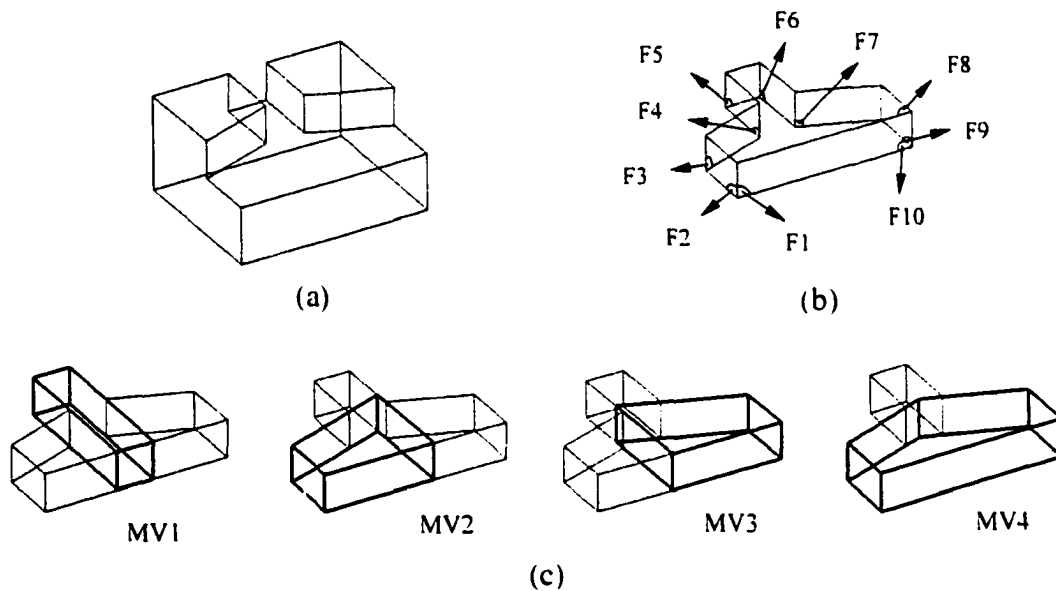


Figure 3.13 (a) part; (b) delta volume; (c) maximal volumes.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
MV1				•	•	•				
MV2		•	•							
MV3							•		•	
MV4	•	•	•				•		•	

Table 3.2 Face containment of maximal volumes in Figure 3.13.

However, the union of unique MVs is often not the delta volume. In Figure 3.14(c), MV1 and MV6 are the only unique MVs, and their union is not the delta volume. Hence, we need to select other MVs so that the union of the selected MVs is the delta volume itself.

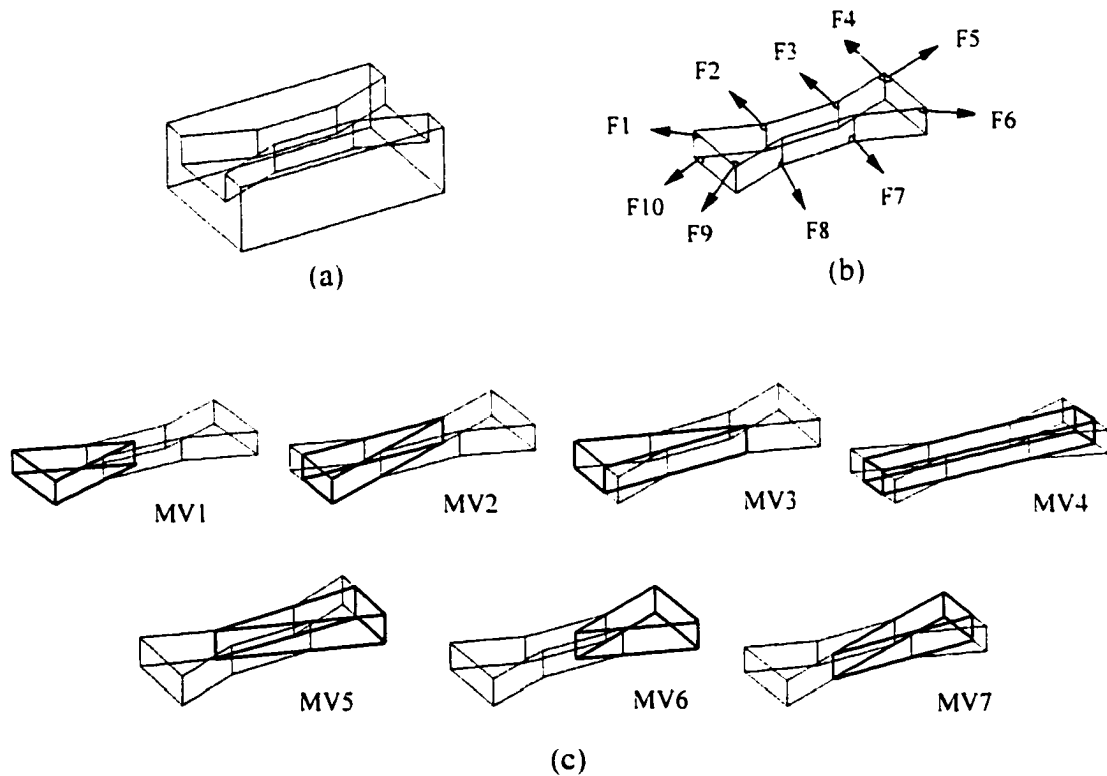


Figure 3.14 (a) part; (b) delta volume; (c) maximal volumes.

When an MV contains a maximal set of faces of a delta volume that are not contained by unique MVs, the MV is said to contain the faces *maximally*. For the delta volume in Figure 3.14(b), $\{MV1, MV2, MV3, MV6\}$, $\{MV1, MV2, MV6, MV7\}$, $\{MV1, MV3, MV5, MV6\}$, $\{MV1, MV5, MV6, MV7\}$ or $\{MV1, MV4, MV6\}$ can be selected as a set of non-redundant MVs. Table 3.3 shows the face containment of each

MV shown in Figure 3.14(c). MV4 contains F3 and F4 that are not contained by the unique MVs. Since no other MV contains the both faces, MV4 contains a maximal set of the faces of the delta volume that are not contained by the unique MVs. Since larger volumes are preferred - this is the purpose of maximal feature recognition, it is more desirable to select MV4 than others. Therefore, by selecting MVs that contain the faces of a delta volume uniquely or maximally, we form a set of non-redundant MVs. MVs in the set are called *effective maximal volumes* (EMVs) hereafter.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
MV1	•	•						•		
MV2			•					•		
MV3		•					•			
MV4			•				•			
MV5			•			•				
MV6				•	•	•				
MV7				•			•			

Table 3.3 Face containment of maximal volumes in Figure 3.14.

3.4.2 Conversion of Unmachinable EMVs into Maximal Features

Since every halfspace of an EMV is a halfspace of the delta volume, each EMV has one or more faces in area contact with part faces. The faces of the part are created with cutters traveling along these EMV faces. In this sense, these EMV faces are *effective* and called *e-faces* hereafter.

For an EMV to be recognized as a maximal feature, it must be machinable in a single setup with a 3-axis machine. Whether an EMV is machinable in a single setup

depends on not only the geometry of the EMV but also the cutters available in a machine shop. Since end-milling cutters are most often used and form cutters are used only in special cases, only parts that can be machined with end-milling cutters and drills are considered in this research.

An EMV is unmachinable in a single setup when (1) not all the part faces in area contact with the EMV can be created in the setup direction, or (2) creating a part face in area contact with the EMV destroys the part. These occur when there is no direction to which every planar e-face is either parallel or perpendicular, and to which the axis of every cylindrical e-face is parallel. For example, EMV1 in Figure 3.15 is machinable in a single setup because all the e-faces are perpendicular to each other. Thus, it is a maximal feature. However, since the slanted face of EMV2 in Figure 3.15 is neither parallel nor perpendicular to other e-faces of EMV2, EMV2 is unmachinable in a 3-axis machine. Such unmachinable EMVs need to be converted into maximal features.

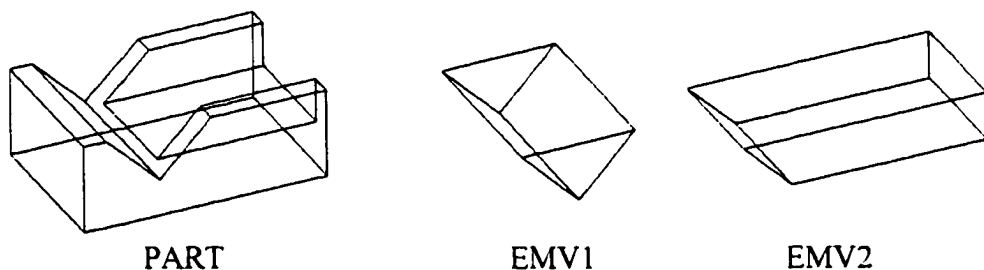


Figure 3.15 Example of unmachinable EMV: EMV2 is unmachinable.

Given the part P and other EMVs, the following is the algorithm for converting an unmachinable EMV denoted by UE into maximal feature(s):

1. Collect machinable EMVs that contain the e-faces of UE .

2. For each planar e-face f of UE .
 - (2-a) generate a volume V_{sw} by infinitely sweeping f in the direction opposite to the normal of f . A face normal is directed toward outside of UE .
 - (2-b) If $V_{sw} \cap P = \emptyset$, generate a volume V_f by intersecting V_{sw} with Δ , and mark f .

3. Check if all the faces of UE are covered by V_f 's and the machinable EMVs that contain the e-faces of UE .
 - (3-a) If so, go to step 5.
 - (3-b) Otherwise, go to step 4.

4. For each unmarked f .
 - (4-a) Generate a volume V_{sw} by infinitely sweeping f in the direction opposite to the normal of f .
 - (4-b) Generate a volume V_i by intersecting V_{sw} with P .
 - (4-c) Generate a bounding box V_b , which is infinitely long in the direction normal to f .
 - (4-d) Generate V_f by subtracting V_b from the intersection of V_{sw} and Δ .

5. Select V_f 's that are not contained by other V_f 's and the machinable EMVs that contain the e-faces of UE .

6. Return the selected V_i 's as maximal features.

In converting EMV2 in Figure 3.15, for example, two V_i 's, V_1 and V_2 , are generated for EMV2 in step 2 as shown in Figure 3.16. Then V_2 is selected in step 5 as the only maximal feature since V_1 is contained by EMV1 in Figure 3.15. Figure 3.17 shows maximal features of the part in Figure 3.15.

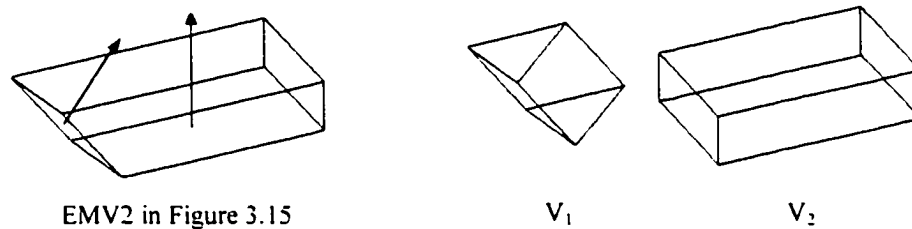


Figure 3.16 Generation of V_i 's.

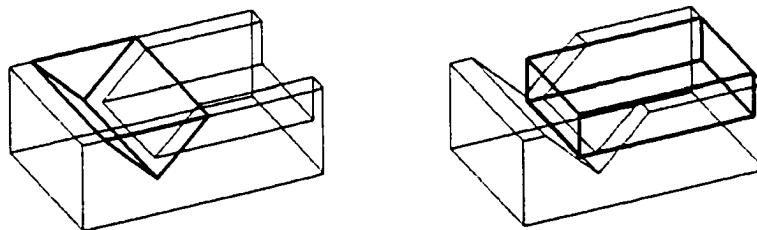


Figure 3.17 Maximal features of the part in Figure 3.15.

Figure 3.18 shows another example of converting unmachinable EMV. The EMV in Figure 3.18(a) is an EMV of the part in Figure 3.8. The EMV is unmachinable since the axis of the cylindrical e-face is neither parallel nor perpendicular to the planar e-face. In converting the unmachinable EMV, first the machinable EMV containing the

cylindrical e-face of the unmachinable EMV is collected in step 1 as shown in Figure 3.18(b). Then V_f is generated from the planar e-face of the unmachinable EMV in step 2. Since the machinable EMV and V_f cover all the faces of the unmachinable EMV, the V_f shown in Figure 3.18(c) is selected in step 5 as the maximal feature.

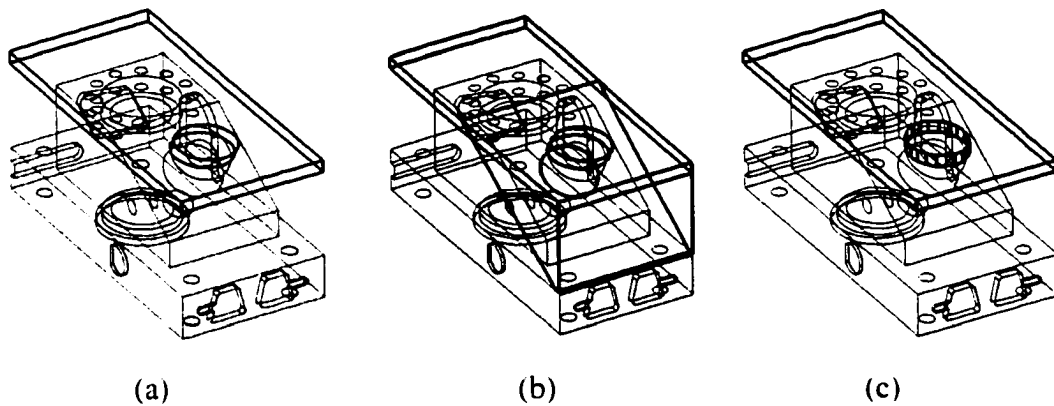


Figure 3.18 (a) Unmachinable EMV of the ANC101 test part; (b) the cylindrical e-face is contained by other EMV; (c) maximal feature covered from the EMV in (a).

The maximal features converted from unmachinable EMVs may have halfspaces that are not halfspaces of the delta volume. This is another exception to the properties of maximal features presented in section 3.2.1.

Chapter 4

Preliminaries for Optimal Plan Generation

4.1 Overview

In this chapter, as a preliminary step to optimal process planning, two important machining parameters, setup directions and cutter sizes, are examined, and the methods to identify setup directions for a machining feature and determine cutter sizes for machining features are presented.

4.2 Identification of Possible Setup Directions for Features

Setup is an operation by which a workpiece is securely fixed and accurately located on a machine table so that cutters can cut the workpiece to machine features. In order to generate the optimal process plan using the feature-based model created by feature recognition, we need to identify setup directions for features. Here a setup direction for a feature is the direction of the cutter axis in which the feature is machined in a 3-axis machining center. An example of the setup direction is shown in Figure 4.1. The setup direction is represented as a unit vector in the part coordinate system.

A feature is to be machined in one setup, but a feature may have more than one possible setup direction. For example, the step feature in Figure 4.2 can be

machined in either of the two directions. However, we cannot simply select one of the setup directions because selecting a setup direction for a feature may affect selecting setup directions for other features. Finding the minimum number of setup directions in which all the features can be machined requires identification of interactions among the features. For this reason, we need to first identify all the possible setup directions for each feature. Then later, one setup direction for each feature will be selected in the phase of plan generation.

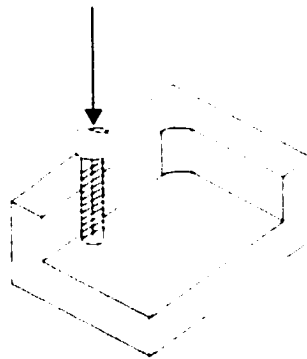


Figure 4.1 Setup direction for a pocket feature.

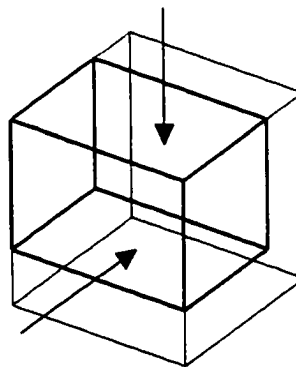


Figure 4.2 Possible setup directions.

In 3-axis machines, the setup direction for a feature should be parallel or perpendicular to the e-faces of the feature. This is a necessary condition for a possible setup direction. Thus, for a feature, first we want to identify directions - called cutter approach directions - that satisfy the following geometric conditions:

1. Every planar e-face of the feature is either parallel or perpendicular to the direction.
2. The axis of every cylindrical e-face of the feature is either parallel or perpendicular to the direction.

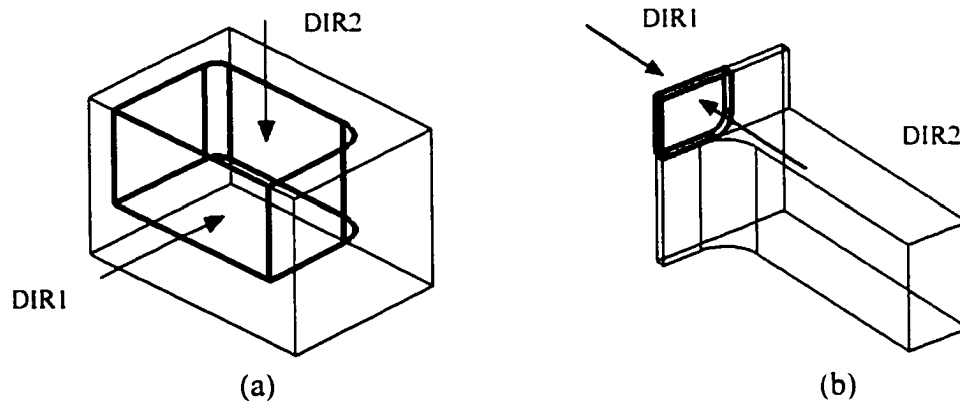


Figure 4.3 Examples of cutter approach directions.

Figure 4.3 shows examples of cutter approach directions. It should be noted that a cutter approach direction is not necessarily a possible setup direction. For a cutter approach direction to be identified as a possible setup direction, the cutter

approach direction should also satisfy the following conditions as well as the geometric conditions:

1. The feature can be accurately machined in the direction.
2. When machining the feature in the direction, the cutter and the spindle should not interfere with the part and fixtures.

For example, the feature in Figure 4.3(a) is not manufacturable in the direction of DIR1 because the linear edges parallel to the direction and circular edges shown in Figure 4.4 cannot be accurately machined. Therefore, in this case, only DIR2 is identified as the possible setup direction. Figure 4.5 shows an example for the second condition. The feature in Figure 4.3(b) is not accessible in the direction of DIR2, since the spindle of the machine hits with the part when a cutter approaches to the feature in the direction as shown in Figure 4.5. Thus, DIR1 is selected as the possible setup direction for the feature.

The accessibility of a feature in a cutter approach direction is related to the lengths of cutters to be used, and the lengths of cutters also depend on the diameters of the cutters. In this research, the accessibility of a feature in a cutter approach direction is checked with the largest cutter possible for machining the feature. The method to select the largest cutters for features is presented in the next section.

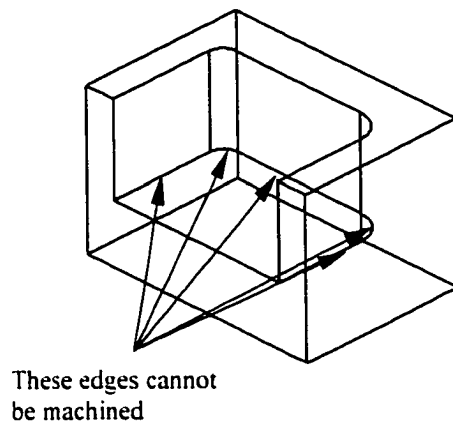


Figure 4.4 Unmachinable edges.

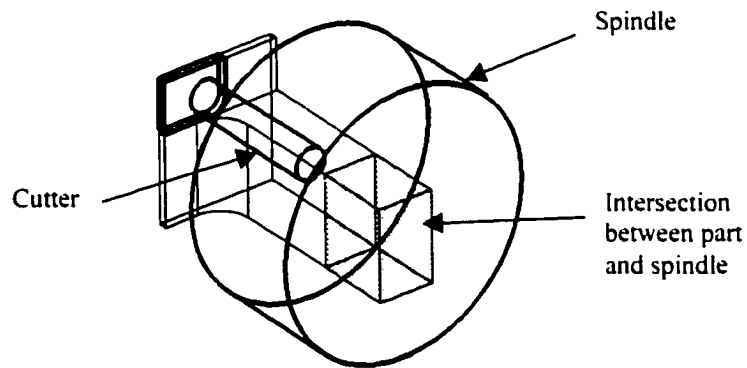


Figure 4.5 Inaccessibility.

4.3 Selection of Maximum Cutter Sizes for Milling Features

4.3.1 Cutters to Be Used

In a milling operation, a larger cutter results in a higher material removal rate and a shorter length of cutter paths^{*}. Therefore, it is more desirable to use as large cutters as possible without destroying a part so that the part can be machined in the

^{*} It is assumed that the machine has enough horsepower.

minimum time. Other machining parameters such as feed rates, speeds, and depth of cut are dependent on the cutter sizes, and they can be obtained by retrieving values from machining parameter tables. For these reasons, in optimizing a process plan it is important to find maximum cutter sizes allowable to machine features.

Usually, two different cutters are used in milling a feature, one for roughing cut and the other for finishing cut. By doing so, it is possible to achieve significant reductions in machining time and cost compared with those resulting from the use of a single cutter to machine the entire feature. With a machining center equipped with automatic tool exchanger, the time needed to change cutters is trivial compared with the total machining time.

4.3.2 Selection of Maximum Cutter Size for Finishing Cut

For a cutter to be used for finishing cut, the cutter should satisfy the following requirements:

1. With the cutter, the feature can be completely machined.
2. Moving the cutter along the contour[†] of the feature does not destroy the part.

For the first requirement, the diameter of a cutter must be equal to or less than the diameter of the smallest fillet of the feature, which is denoted by D_c . To satisfy the second requirement, the diameter of a cutter must be equal to or less than the

[†] The profile of a feature is defined as the cross section of the feature cut by the plane whose normal is parallel to the setup direction. And the collection of the edges of the profile is defined as the contour. When a milling feature is machined with a flat end-mill cutter, the collection of the edges of the face created by the end of the cutter is the contour.

smallest distance between two points in two disjoining edges of the contour. This smallest distance is called minimum passage and denoted by D_p . Maximum cutter diameter for finishing cut, D_{finish} , is the smaller value of the diameter of the smallest fillet and minimum passage. That is:

$$D_{finish} = \min(D_c, D_p).$$

4.3.2.1 Finding the Diameter of the Smallest Fillet, D_c

In the profile of a milling feature, the smallest fillet can be found by searching the circular edge with the smallest diameter. Then the diameter is selected as D_c . When there is a sharp corner whose diameter is zero in the profile, the cutter of the smallest diameter should be selected.

When features intersect, however, the features may have sharp corners that do not exist in the delta volume. For example, the slot and pocket features in Figure 4.6(c) intersect each other. The pocket has a sharp corner that does not exist in the delta volume in Figure 4.6(b). If that corner is detected as a sharp corner, a cutter of the smallest diameter (A in Figure 4.6(d)) should be selected, though the pocket feature can be machined with a cutter of larger diameter (B in Figure 4.6(d)). Thus this kind of sharp corner, called virtual corner, should be distinguished from ordinary sharp corners.

- **Detection of Virtual Corners**

For an edge of the contour of a milling feature, if the wall face of the edge, which is generated by sweeping the edge in the cutter approach direction, is in area contact with the part, the edge is called closed edge. Otherwise, it is called open edge. For example, Figure 4.7(a) shows the closed and open edges of the pocket feature in Figure 4.6(c).

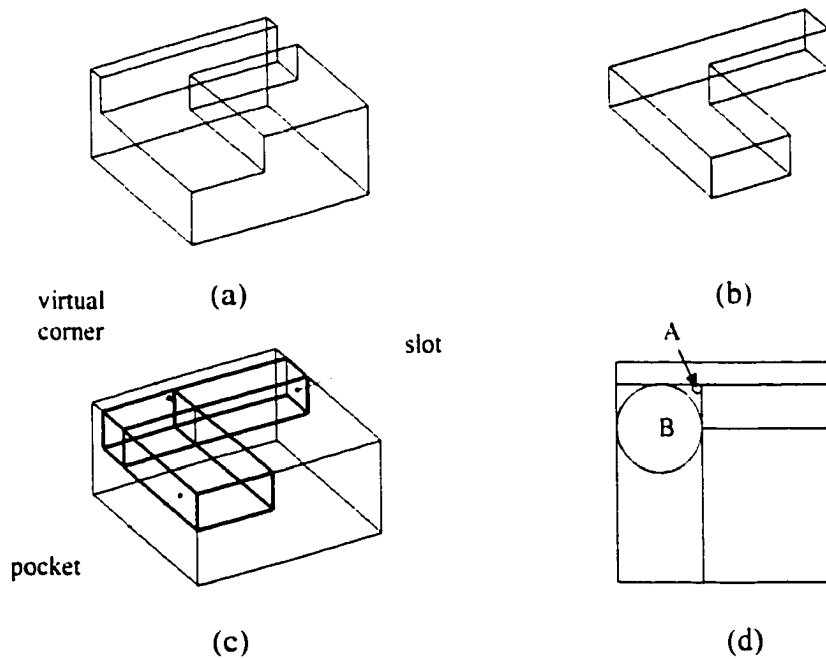


Figure 4.6 Existence of virtual corner: (a) part; (b) delta volume; (c) pocket and slot features and virtual corner of the pocket feature; (d) different sizes of cutters shown in the top view.

Figure 4.7 shows the process of detecting virtual corners of the pocket feature in Figure 4.6(c). Detection of virtual corners begins with identification of closed edges of the contour. It is done by checking if the wall face of each edge of the contour is in area contact with the part. If so, it is a closed edge. Otherwise, it is an

open edge. Next, the contour is modified by segmenting the closed edges of the contour. If there are part vertices that lie inside a closed edge, the closed edge is segmented by inserting the vertices to the edge (Figure 4.7(b)). The modified contour is then swept in the cutter approach direction, and each segment is examined if it is an open edge (Figure 4.7(c)). If one or both of the edges forming a sharp corner is an open edge, the sharp corner is the virtual corner.

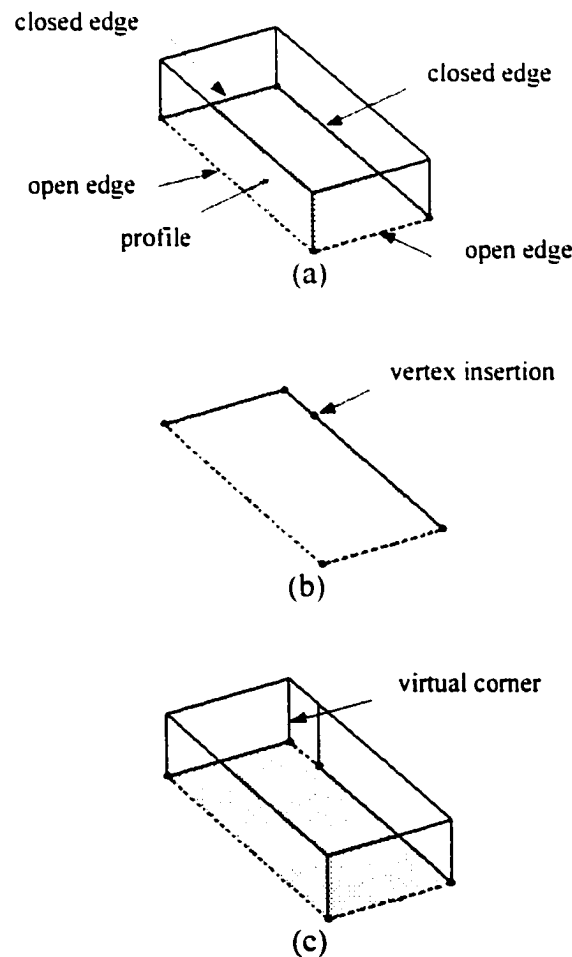


Figure 4.7 Virtual corner detection: (a) identification of closed edges; (b) segmentation of the closed edge; (c) sweeping of the modified profile.

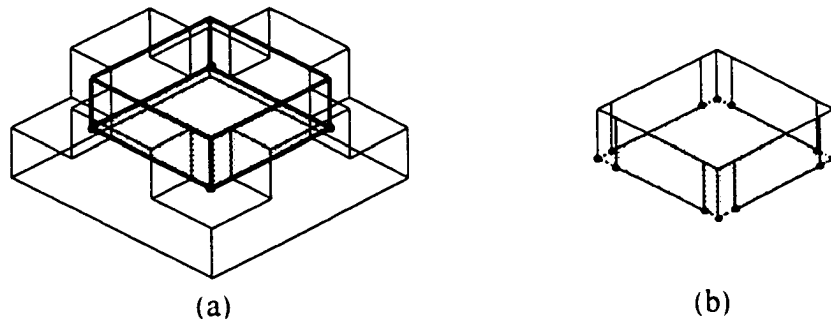


Figure 4.8 Virtual corner detection: (a) a part and its feature: (b) four virtual corners detected.

Figure 4.8 shows another example of virtual corners. For the pocket in Figure 4.8(a), each of the corners is identified as a virtual corner. In this case, each virtual corner is formed by two open edges.

• Calculation of Diameters for Virtual Corners

The diameters for virtual corners shown in Figure 4.9 are calculated as follows:

$$\text{Diameter} = 2l_1 \tan\left(\frac{\cos^{-1}(\mathbf{n}_1 \cdot \mathbf{n}_2)}{2}\right),$$

where l_1 = length of the shortest open edge, and

$\mathbf{n}_1, \mathbf{n}_2$ = directions of the edges in unit vectors.

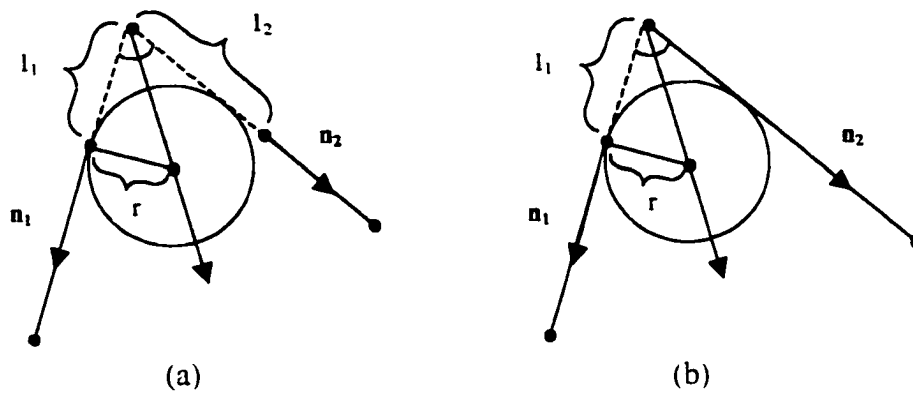


Figure 4.9 Calculation of diameters for virtual corners: (a) virtual corner formed by two open edges; (b) virtual corner formed by an open edge and a closed edge.

4.3.2.2 Finding Minimum Passage, D_p

Minimum passage is found by calculating the minimum distance between two points in two disjointing closed edges with the condition that the line connecting the two points should be inside of the profile. Examples of the minimum cutter passages for milling features are shown in Figure 4.10.

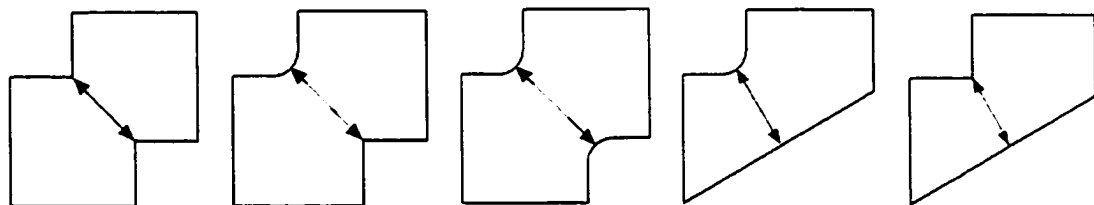


Figure 4.10 Examples of minimum passages.

4.3.3 Selection of Maximum Cutter Size for Roughing Cut

A cutter to be used for roughing cut should satisfy the following requirements:

1. Finishing cut can completely remove the remaining volume of the feature after the roughing cut with the cutter.
2. Moving the cutter within the profile does not destroy the part.

The size of the roughing cutter depends on the size of the finishing cutter. To satisfy the first requirement, the diameter of a roughing cutter should be equal to or less than the diameter, D_r , of the circle that is in contact with not only two edges forming the corner but also the circle of the finishing cutter as shown in Figure 4.11. To satisfy the second requirement, the diameter of a roughing cutter should be equal to or less than the minimum passage D_p . The maximum diameter, D_{rough} of a roughing cutter, D_{rough} is the smaller value of D_r and D_p . That is:

$$D_{rough} = \min(D_r, D_p).$$

• Calculation of D_r

- (1) At a sharp corner or a corner with the fillet whose radius is the same as the radius of the finish cutter,

$$D_r = 2R = 2r \frac{1 + \cos \alpha}{1 - \cos \alpha},$$

where r = radius of the cutter for finishing cut,

$$\alpha = \frac{1}{2} \cos^{-1}(\mathbf{n}_1 \cdot \mathbf{n}_2), \text{ and}$$

$\mathbf{n}_1, \mathbf{n}_2$ = directions normal to the edges in unit vectors.

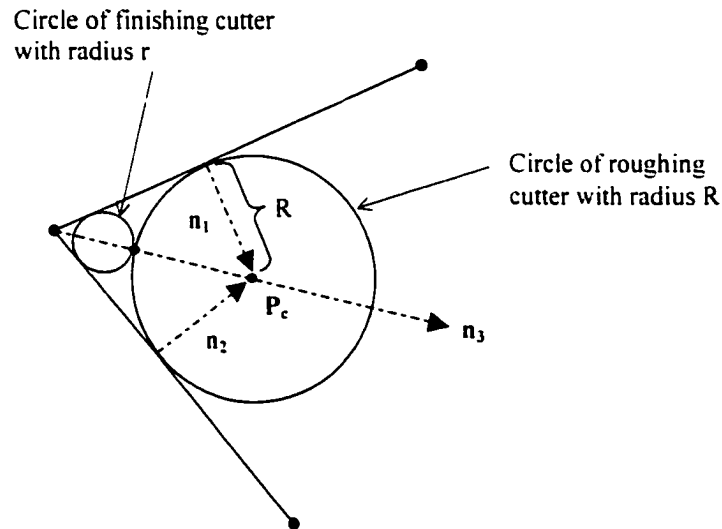


Figure 4.11 Calculation of maximum cutter size for roughing cut at a sharp corner.

- (2) At a corner with the fillet whose radius is larger than the radius of the finishing cutter.

$$D_r = 2R = 2r \frac{1 + \cos \alpha - R_f \cos \alpha}{1 - \cos \alpha},$$

where r = radius of the cutter for finishing cut,

R_f = radius of the fillet,

$$\alpha = \frac{1}{2} \cos^{-1}(\mathbf{n}_1 \cdot \mathbf{n}_2), \text{ and}$$

$\mathbf{n}_1, \mathbf{n}_2$ = directions normal to the edges in unit vectors.

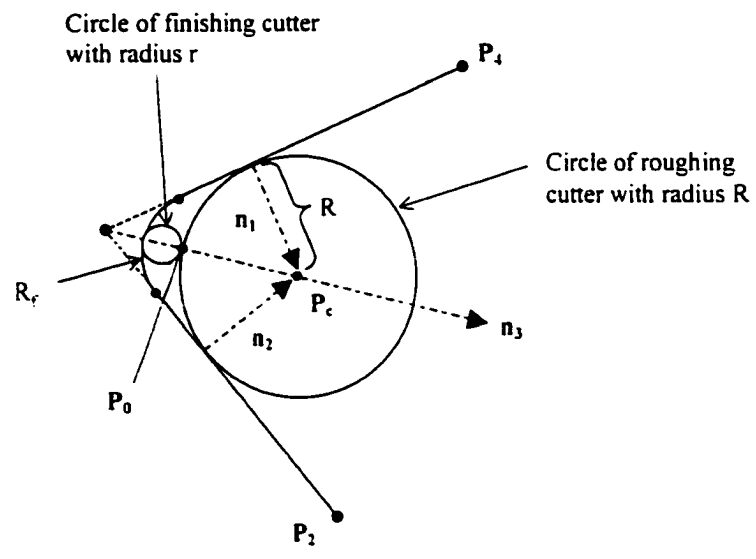


Figure 4.12 Calculation of maximum cutter size for roughing cut at a corner with the fillet.

Chapter 5

Generation of Optimal Plans

5.1 Overview

In this chapter, a method to generate the optimal process plans for machined parts using maximal features is presented. The next section presents a brief explanation of the method, and each step of the method is explained in details in the following sections.

5.2 Outline of the Method

Figure 5.1 shows the steps of the method to generate the optimal process plan with the feature-based model.

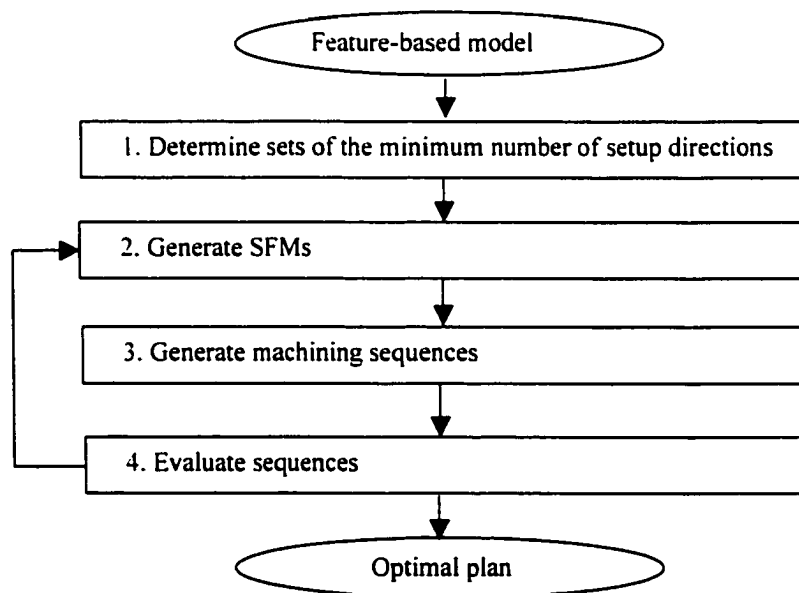


Figure 5.1 Generation of the optimal process plan.

(1) Determine sets of the minimum number of setup directions

The first step is to determine the sets of the minimum number of setup directions in which a part can be completely machined. For the example part in Figure 5.2, not all the three setup directions are necessary. In this case, either of two sets of setup directions $\{\text{Dir1}, \text{Dir3}\}$ and $\{\text{Dir2}, \text{Dir3}\}$ can be used to completely machine the part. Thus, these two sets are the sets of the minimum number of setup directions.

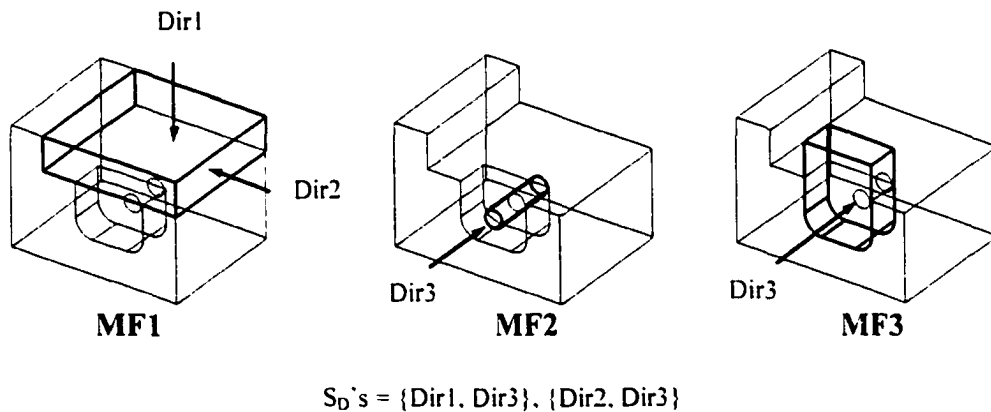


Figure 5.2 An example part and its three maximal features: arrows indicate setup directions possible for each maximal feature.

(2) Generate Setup-based Feature Models (SFMs)

Machining MF1 in Figure 5.2 in the setup direction of Dir1 is different from machining it in the direction of Dir2. Therefore, we need to generate feature-based models in which each feature is associated with one setup direction. These models are called SFMs, where *S* stands for setup direction and *FM* stands for feature-based model. Figure 5.3 shows two SFMs for the part in Figure 5.2.

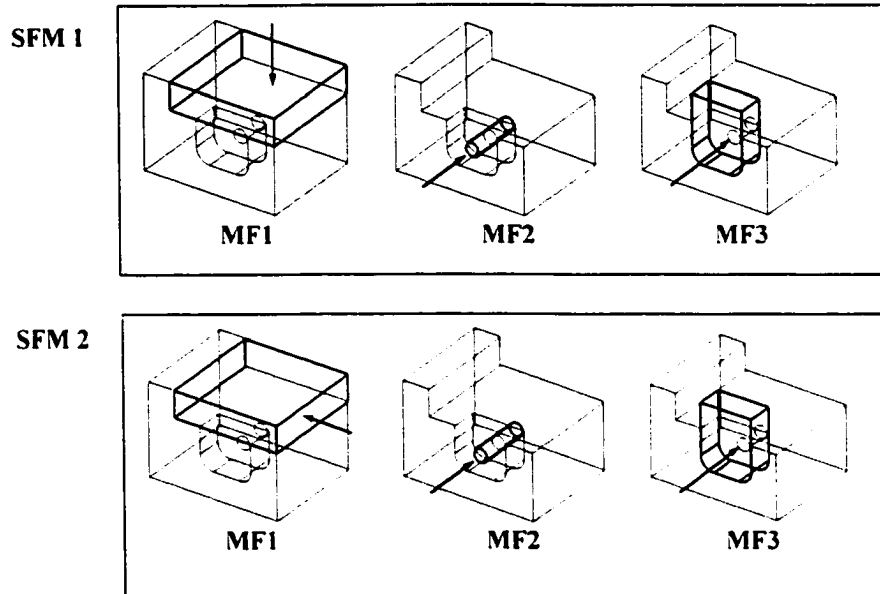


Figure 5.3 Two SFMs for the part in Figure 5.2.

(3) Generate machining sequences

In this step, machining sequence of maximal features in each SFM is determined. Various rules are used in identifying constraints on the machining sequence of features. These constraints are called precedence constraints. For each SFM, maximal features in each setup direction are first sequenced based on the precedence constraints and then setup directions are sequenced again based on the precedence constraints. Figure 5.4 shows the precedence constraints among maximal features in SFM1 and SFM2 respectively. According to the precedence constraints, the part is to be created by machining MF1 → MF3 → MF2 for both SFM1 and SFM2. Non-overlapping ordered features are generated based on the sequence.

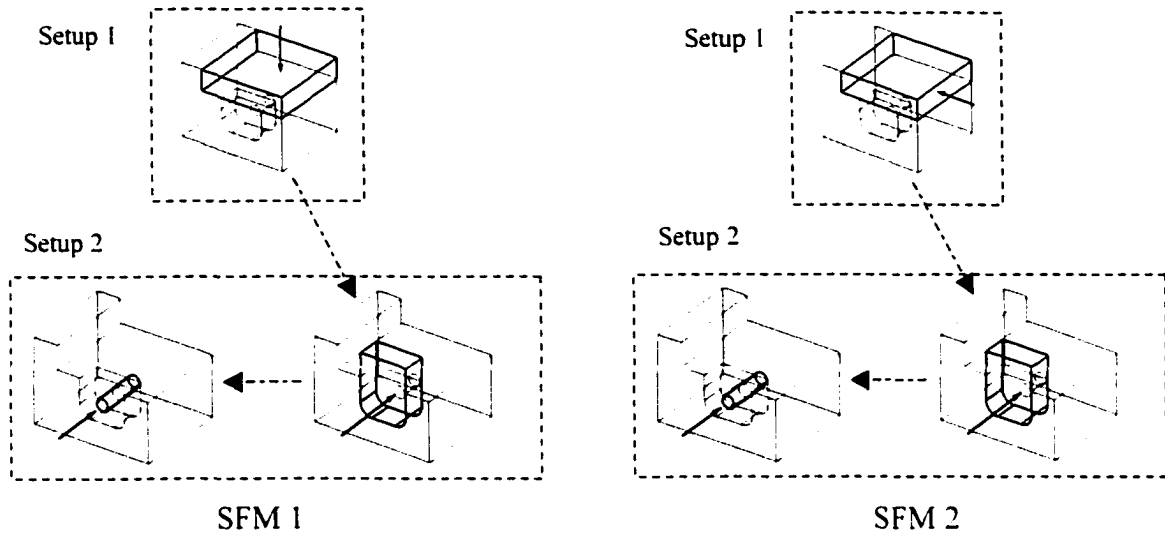


Figure 5.4 Precedence constraints.

(4) Evaluate machining sequences and select the best one

In this step, machining time for each machining sequence is estimated based on the non-overlapping ordered features and machining sequence. The machining sequence that requires the minimum machining time is selected as the optimal process plan for the part.

5.3 Determination of Sets of the Minimum Number of Setup Directions

Whenever a new setup is required, the machinist has to relocate the workpiece by removing it from the fixture, orienting it in another setup direction, and fixing it accurately. Therefore, it is important to minimize the number of setups in machining a part. The less number of setups not only reduces the cost and machining time but also improves the dimensional accuracy of the part.

To minimize the number of setups, we need to determine the sets of the minimum number of setup directions. There is a case where one setup direction is used in more than one setup. In such a case, the number of setups is greater than the number of minimum setup directions.

Figure 5.5 shows the process of determining the sets of the minimum number of setup directions. This process is explained with the example part in Figure 5.6. There are three setup directions for the maximal features in Figure 5.6. Each of the subsets having one setup direction, i.e., {Dir1}, {Dir2}, and {Dir3}, is first generated and checked if the part can be completely machined. As the part cannot be machined in any of the directions, each of the subsets having two setup directions, i.e., {Dir1, Dir2}, {Dir1, Dir3}, and {Dir2, Dir3}, is then generated and checked if the part can be completely machined. Since the part can be completely machined in the setup directions of {Dir1, Dir2}, and the directions are selected as a set of minimum number of setup directions. Next, the part is checked if it can be completely machined in the setup directions of {Dir1, Dir3} or {Dir2, Dir3}. Since the part cannot be completely machined in the setup directions of either of the sets, process terminates. Therefore, {Dir1, Dir2} is the only set of the minimum number of setup directions for the part.

There are cases where multiple sets of minimum number of setup directions are possible. An example for this case is the maximal features in Figure 5.2. The sets of minimum number of setup directions are denoted by S_D 's hereafter.

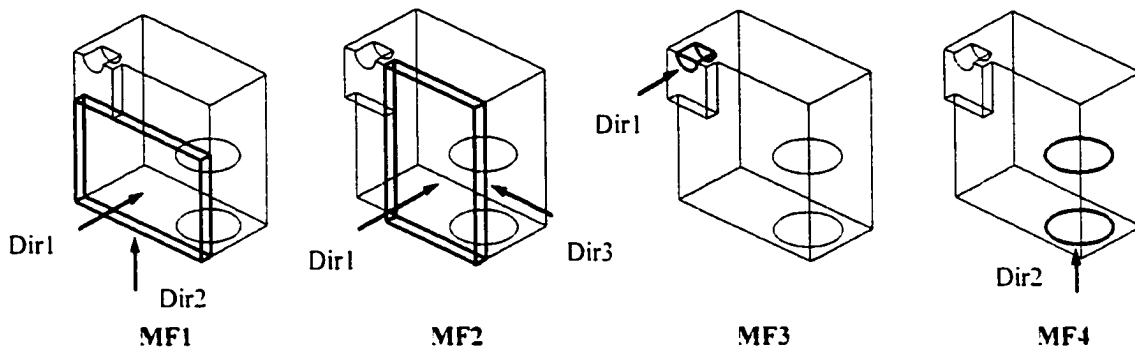


Figure 5.6 Maximal features of a part with possible setup directions.

5.4 Generation of SFMs

A maximal feature may have more than one possible setup directions in an S_D . For example, MF1 in Figure 5.6 can be machined either in the direction of Dir1 or in the direction of Dir2. In which direction should the feature be machined? At this point, which direction results in a better plan is unknown.

When a feature has more than one possible setup direction in an S_D , machining the feature in different setup directions results in different process plans. To generate the optimal process plan, it is necessary to evaluate all the different plans. To do so, we first generate feature-based models each of whose features is associated with one setup direction. These models are called SFMs hereafter. In an SFM, one feature has only one possible setup direction.

There are two cases where maximal features of a part lead to multiple SFMs. One is when there are multiple S_D 's and the other is when a maximal feature has more than one possible setup direction in an S_D . An example of the first case is the maximal

features in Figure 5.2. Because of two S_D 's, two SFMs are generated as shown in Figure 5.3. The maximal features in Figure 5.6 shows an example of the second case. Since MF1 can be machined either in the direction of Dir1 or in the direction of Dir2, two SFMs are generated as shown in Figure 5.7.

If maximal features MF_1, MF_2, \dots, MF_m have n_1, n_2, \dots, n_m possible setup directions respectively in an S_D , theoretically $(n_1 \times n_2 \times \dots \times n_m)$ SFMs are possible. However, it would be undesirable to consider every SFMs in generating optimal plan when many of the SFM's are practically the same or invalid for machining. In the following section, a method to reduce the number of SFMs by pruning such SFMs is presented.

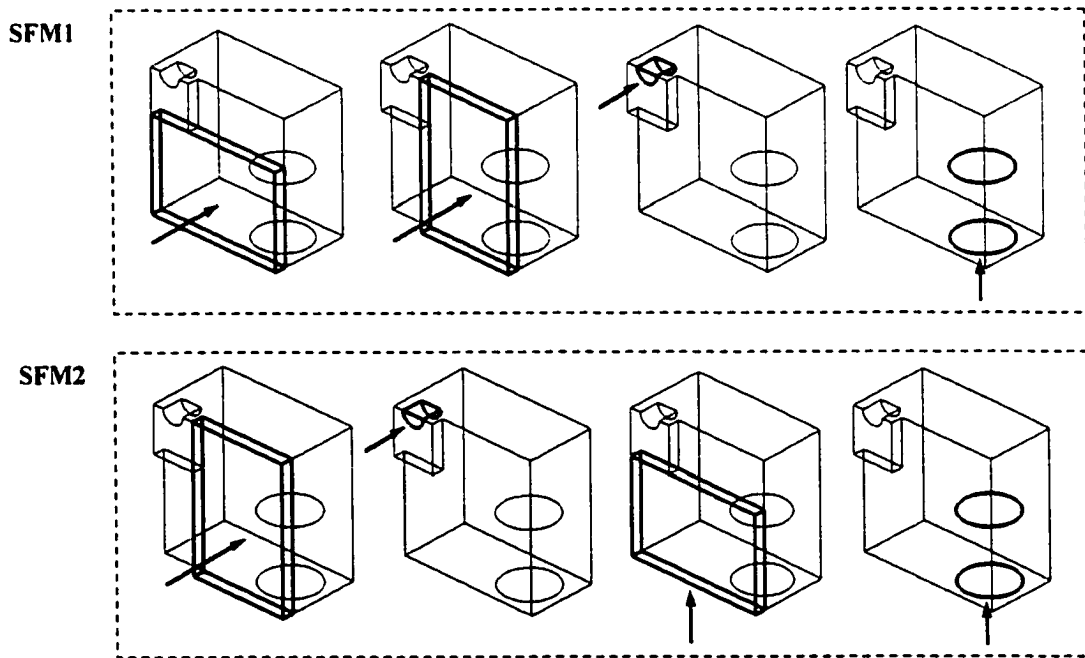


Figure 5.7 Two SFMs for the part in Figure 5.6.

5.4.1 Pruning Unpromising SFMs

Figure 5.8 shows an example part and its maximal features. There is only one S_D for the part. However, since each of MF3 and MF4 can be machined in the direction of either Dir1 or Dir3, four SFMs can be generated as shown in Figure 5.9. No machinist, however, creates the two holes of the same diameter in different setups as shown in SFM2 and SFM3. SFM2 and SFM3 are unpromising in generating the optimal process plan.

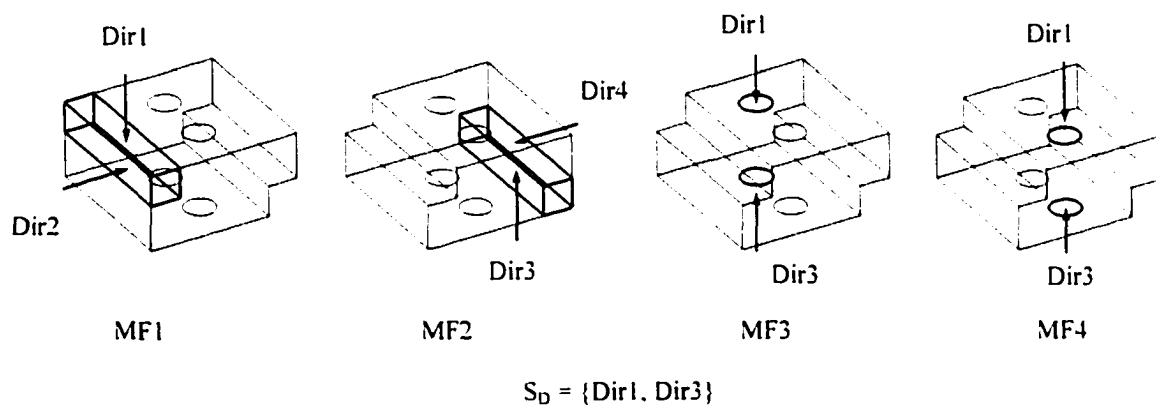


Figure 5.8 A part, maximal features and S_D .

The following two cases, though there may be others, are considered in pruning unpromising SFMs: cutter size and functionality. When drilling features can be machined with the same cutter, it is better to machine the drilling features in the same setup. Therefore, drilling features that can be machined with the same cutter in the same setup direction are grouped together, and they are treated as one feature in generating SFMs. For example, the two drilling features in Figure 5.8 can be machined in the same setup direction and can be created with one cutter. By treating them as one feature, only SFM1 and SFM4 in Figure 5.9 are generated.

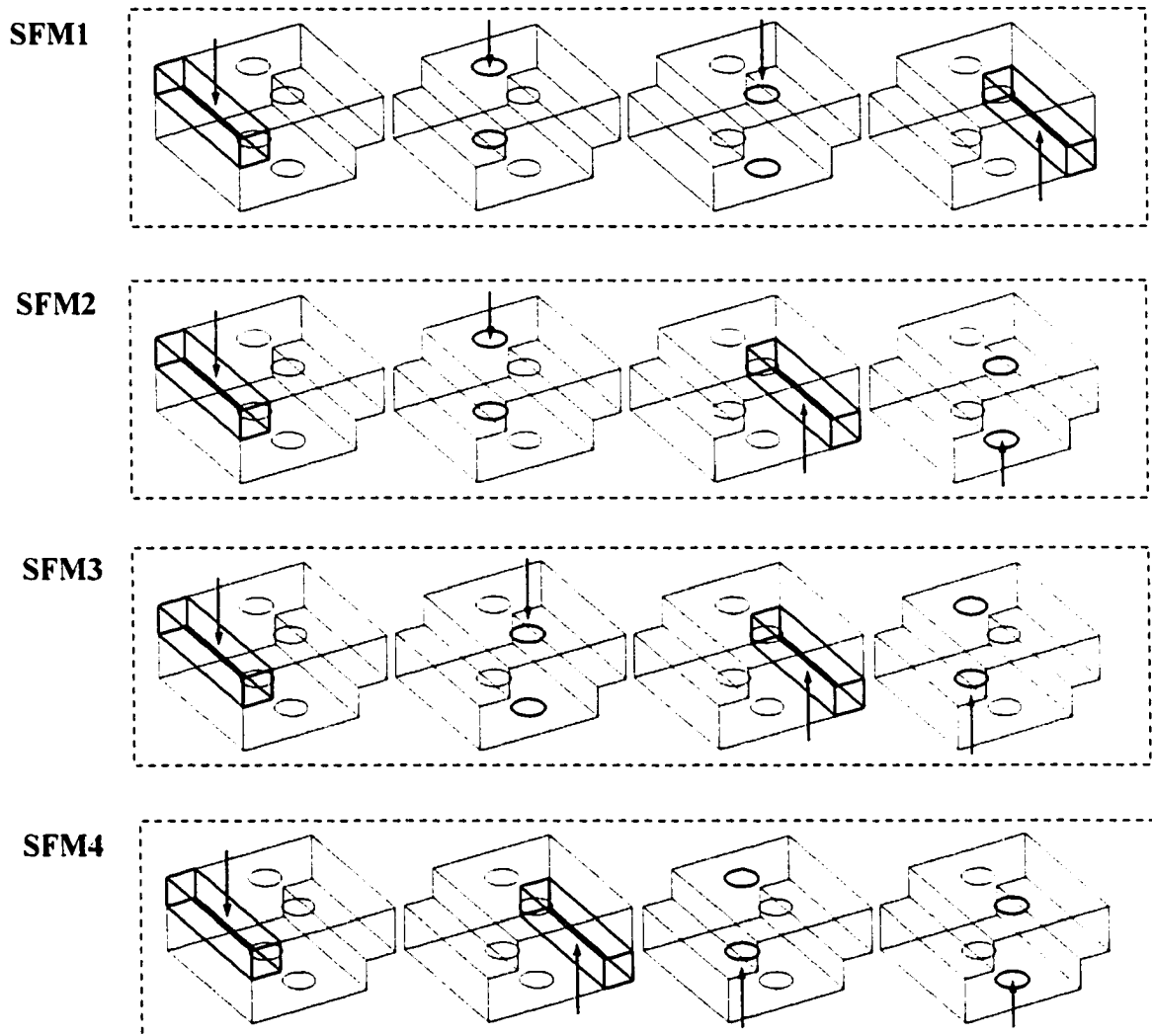


Figure 5.9 SFMs for the part in Figure 5.8.

Another case considered in pruning unpromising SFMs is functionality. Figure 5.7 shows an example of SFMs that can be pruned by functionality. Though MF1 in Figure 5.6 can be machined either in the direction of Dir1 or in the direction of Dir2, no one probably creates the part by machining the features with SFM2. It is because MF1 shares the same part face that can be machined with MF2 in the direction of Dir1. A part face has its functionality and it would be more desirable to create the face in the same

setup. Thus, by treating MF1 and MF2 as one features that is to be machined in the direction of Dir1, SFM2 in Figure 5.7 is pruned.

5.5 Generation of Plans

In this step, a plan is generated from each SFM by merging some features, if preferable, and then by determining the machining sequence. Next, non-overlapping ordered features are generated based on the sequence.

5.5.1 Merging Features

When features share the same planar part face whose normal is parallel to the setup direction, it is often more desirable to machine them as one feature. Machining such features at the same time can reduce machining time because it requires fewer changes of tools and less traveling for the tool changes.

One important factor in merging features into one feature is the sizes of cutters to be used in machining the features. If the differences of cutter sizes are great, it is more efficient to machine each feature with a cutter suitable for the feature. For example, MF1 in Figure 5.10 can be machined with cutter 1. However, merged feature of MF1 and MF2 should be machined with cutter 2 whose diameter is smaller than that of cutter 1. It will take more time to machine the merged feature. So, MF1 and MF2 are not merged in this case.

Figure 5.11 shows another example. Two features in Figure 5.11 are of the same feature types as the features in Figure 5.10. But the merged feature of MF1 and MF2 does not require different cutters. Therefore, MF1 and MF2 are merged in this case.

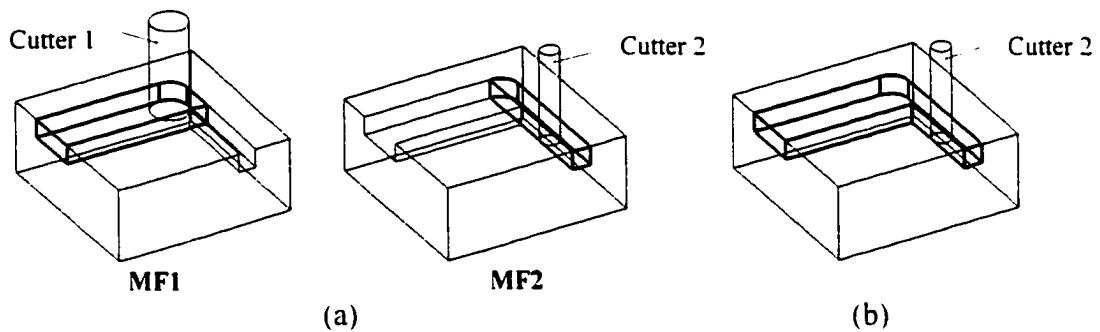


Figure 5.10 An example of undesirable merging of features due to cutter sizes: (a) two open pockets in an SFM with different cutter sizes; (b) merged feature.

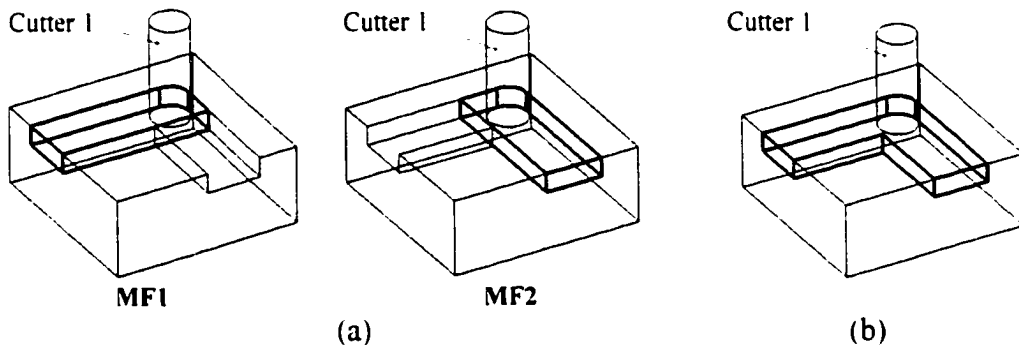


Figure 5.11 An example of desirable merging of features: (a) two open pockets in an SFM with the same cutter size; (b) merged feature.

In addition to the cutter sizes, one thing we need to consider in merging features is the geometry of the features. A feature of simple geometry such as slot can be machined by a single pass of a cutter. Thus, merging such features is not desirable. Example of this case is shown in Figure 5.12. The two features in Figure 5.12(a), slot and step, are features of simple geometry, and they can be machined with simple straight cutter paths. But the merged feature shown in Figure 5.12(b) requires a more complex cutter path and more time to be machined. In this case, merging features is not desired.

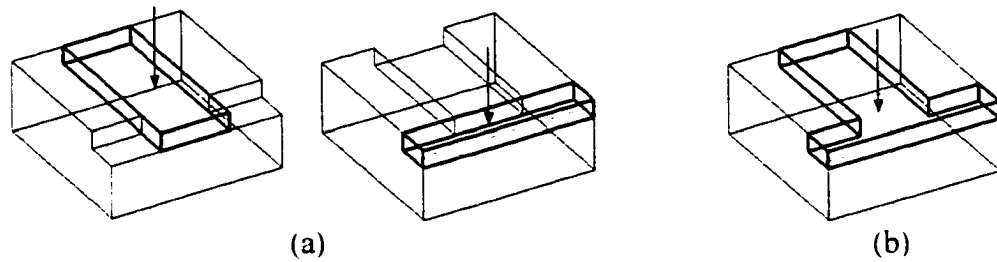


Figure 5.12 An example of undesirable merging of features due to the geometry of the features. The dotted lines show cutter paths: (a) slot and step features in an SFM; (b) merged feature.

Maximal features in an SFM are merged if they satisfy the following conditions:

- 1) They overlap one with another.
- 2) Their setup directions are the same.
- 3) They share the same planar part face whose normal is parallel to the setup direction.
- 4) None of them is a slot.
- 5) None of them is a step feature, or all of them are step features.
- 6) The difference of finishing cutter sizes for the features is within 10 percent of the larger cutter size.

5.5.2 Generation of Machining Sequence

For each SFM, different plans can be generated by sequencing setup directions and features in each setup direction in different orders. If an SFM has n setup directions, and each setup direction has m features, then theoretically there are $n! \times m!$ alternative

plans. For example, if an SFM has three setup directions, and each setup direction has four features, 144 plans are possible. For an SFM having a large number of setup directions and features, the number of alternative plans becomes huge. Therefore, the approach of generating all the plans possible plans for SFMs, evaluating the plans, and selecting the best plan is infeasible.

Setup directions and maximal features in an SFM cannot be sequenced arbitrarily because of various constraints on machining such as cutter accessibility and machining capability and efficiency. By applying the constraints, the generation of invalid or unpromising plans can be avoided. This reduces the number of plans to be generated significantly. Then the optimal plan is selected by evaluating only a small number of promising plans.

5.5.2.1 Identifying Precedence Constraints among Maximal Features

Features often cannot be machined in an arbitrary order. For example, when the milling feature in Figure 5.13(a) is machined before the drilling feature, a drill bit tends to bend on the slanted face in creating the drilling feature. Thus the drilling feature should be machined first, and then the milling feature should be machined. In generating machining sequences, this kind of precedence constraints among features that physically intersect are considered.

Precedence constraints can be identified by examining the feature interactions with consideration of various machining rules. There are two kinds of machining rules: capability-based machining rules and efficiency-based machining rules. Capability-based machining rules result from machining capability. These rules are strict in the sense that

they should be complied in any circumstances. Examples of capability-based machining rules are shown in Figure 5.13. In Figure 5.13(b), the counter-bore feature MF1 should be machined after the drilling feature MF2, because the counter-bore feature is created by boring the hole. In Figure 5.13(c), MF1 should be machined before MF2, because MF2 cannot be fully machined with a cutter having the radius of the fillet. By machining MF1 before MF2, the length of MF2 in the setup direction is reduced, so the remaining volume of the feature can be fully machined with the cutter.

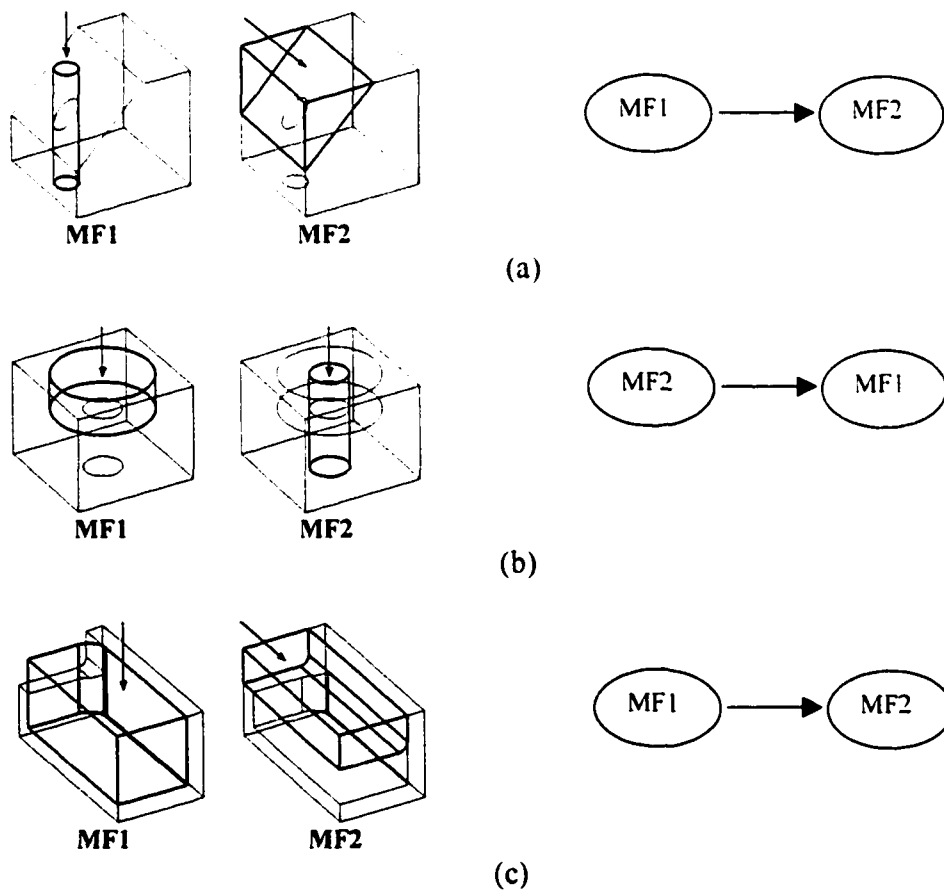


Figure 5.13 Examples of capability-based machining rules.

Efficiency-based machining rules come from the consideration of orders of machining operations that may result in more efficient plans. These rules may be violated in cases where conflicting rules apply. Examples of efficiency-based rules are shown in Figure 5.14. In Figure 5.14(a), machining MF1 reduces the height of MF2, so it is preferred to machine MF1 before MF2. In Figure 5.14(b), machining either of the features does not reduce the height of the other feature. However, since machining MF2 before MF1 changes the length of MF1, it is preferred to machine MF2 before MF1.

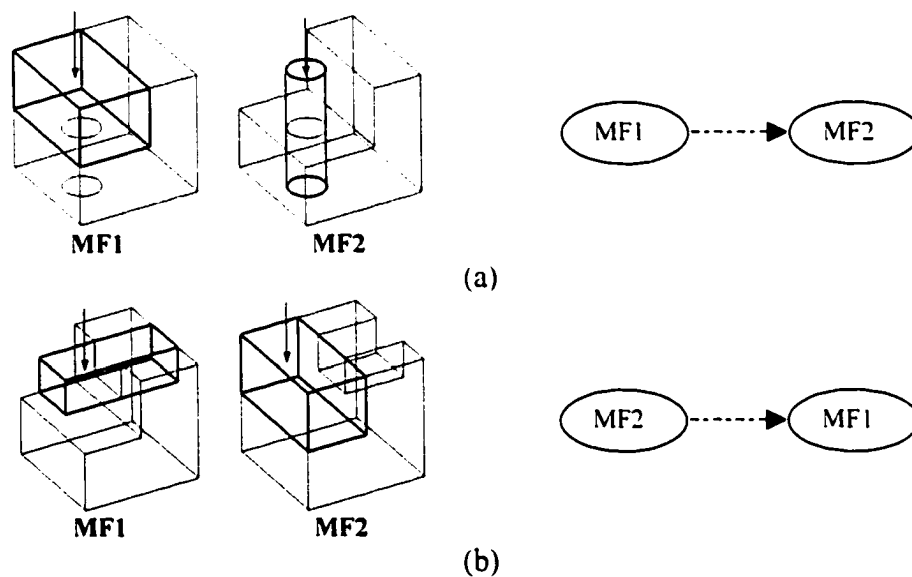


Figure 5.14 Examples of efficiency-based machining rules.

Precedence constraints are identified for two features that physically intersect each other. However, there may be no precedence constraint for two features even though they intersect each other. An example of this case is shown in Figure 5.15.

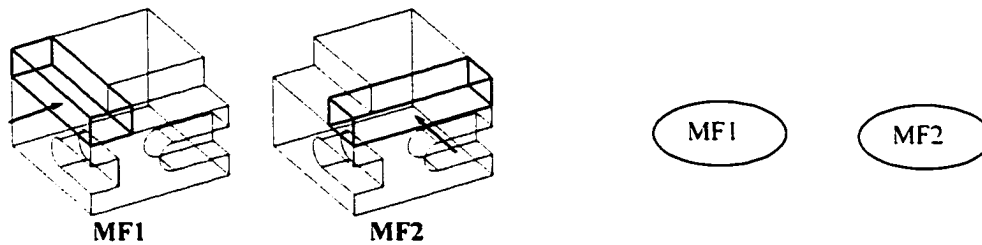


Figure 5.15 Intersecting features with no precedence constraint.

We assign a number to each machining rule. The number represents the priority of the rules (a smaller number means a higher priority). These numbers are inherited to precedence constraints so that the number can be used in cases where precedence constraints conflict in determining machining sequences.

5.5.2.2 Sequencing Maximal Features in Each Setup Direction

After precedence constraints are identified for maximal features, maximal features in each setup direction are sequenced so that the sequence conforms to the precedence constraints. To do so, a table called precedence constraints table (PCT) is generated for the features in the setup direction. A PCT contains precedence constraints and priority numbers of the precedence constraints. For example, Figure 5.17(a) shows PCT for features in the setup direction 1 in Figure 5.16(b), and Figure 5.17(b) shows the graphical representation of the PCT. In the PCT, 1 means that the feature in the row has the precedence over the feature in the column, and 2 means that the feature in the column has the precedence over the feature in the row. The numbers in parenthesis are the priority

numbers. Likewise, Figure 5.18 shows PCT for features in the setup direction 2 in Figure 5.16 and its graphical representation.

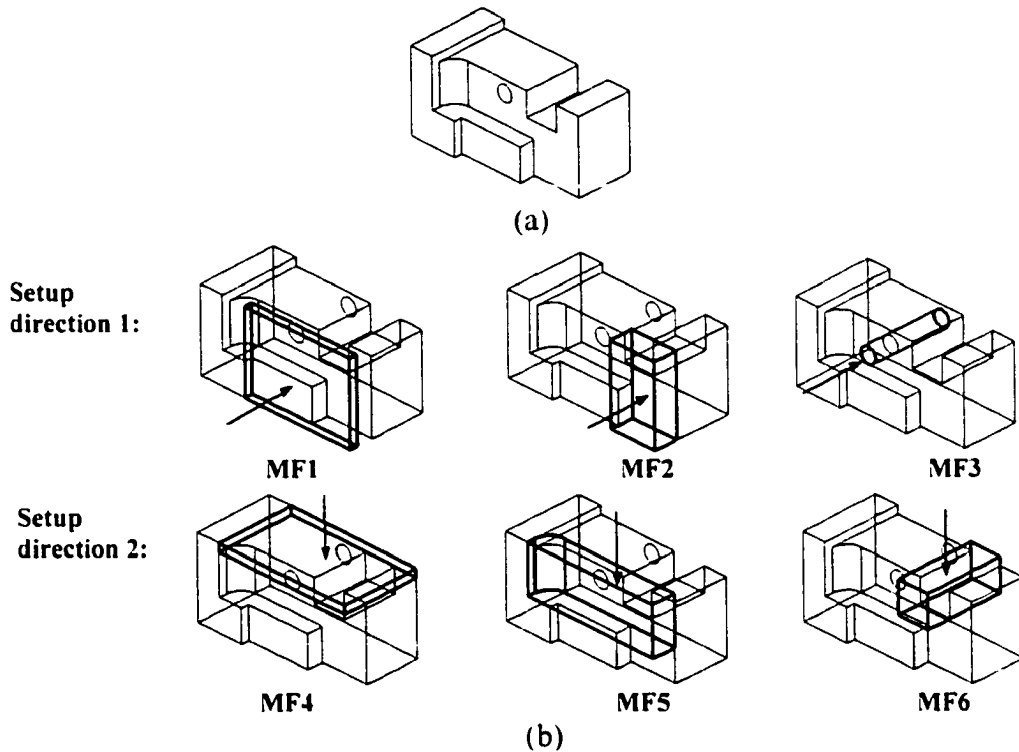


Figure 5.16 (a) a part: (b) SFM of the part.

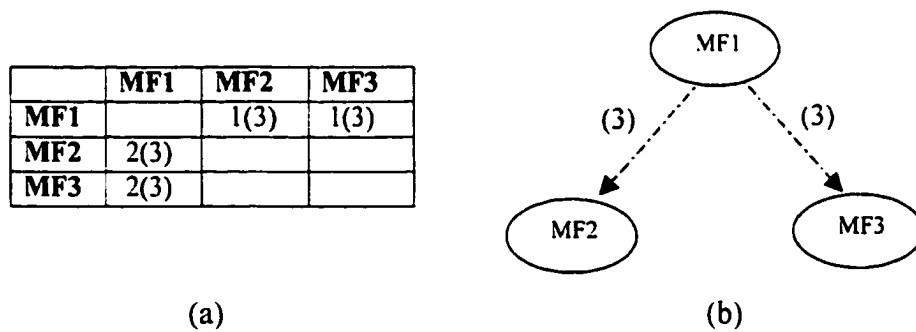
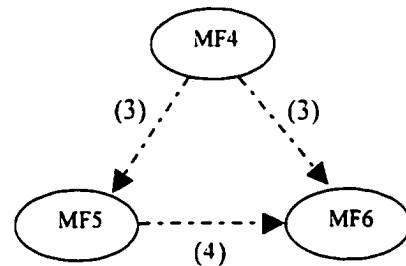


Figure 5.17 (a) PCT for features in setup direction 1 in Figure 5.16; (b) graphical representation of the PCT in (a).

	MF4	MF5	MF6
MF4		1(3)	1(3)
MF5	2(3)		1(4)
MF6	2(3)	2(4)	

(a)



(b)

Figure 5.18 (a) PCT for features in setup direction 2 in Figure 5.16; (b) graphical representation of the PCT in (a).

Upon completion of PCT, a maximal feature that does not have any 2 in its row in the PCT is selected, i.e., in the graphical representation, a maximal feature that does not have incoming arc is selected. There can be a case, however, where more than one maximal feature does not have 2. In such a case, alternative plans can be generated by sequencing them in different orders. But many of the plans tend to be practically very similar and have little differences in machining time. Thus, when there are more than one feature that do not have incoming arcs, the feature that can be machined with the largest cutter is selected. It is because the overlapping volume can be machined more quickly with a larger cutter.

After a feature is selected, it is marked so that it will not be considered again. To the remaining features, the same process is applied to search a feature to be machined next. This process is repeated until all the features are selected, and the order of the selection is the machining sequence for the features in the setup direction.

For example, MF1 in Figure 5.17 is the only feature that has no precedence. Thus MF1 is selected first. After the selection of MF1, MF2 and MF3 have no precedence

because MF1 is not further considered. Since MF2 can be machined with a larger cutter, MF2 is selected first. Thus, the machining sequence for the features is MF1 → MF2 → MF3. Similarly, the features in Figure 5.18 should be machined in the order of MF4 → MF5 → MF6 based on the precedence constraints.

5.5.2.3 Sequencing Setup Directions

Sequencing setup directions is a process similar to sequencing features in each setup direction. Sequencing setup directions begins with identifying precedence constraints among features in every pair of setup directions. The precedence constraints among the features in two setup directions are identified in the same way as in sequencing features in each setup direction. Between two setup directions, four different cases of precedence constraints are possible as shown in Figures 5.19(a) to 5.19(d). In the figures, the solid arrows represent capability-based precedence constraints, and dotted arrows represent efficiency-based precedence constraints.

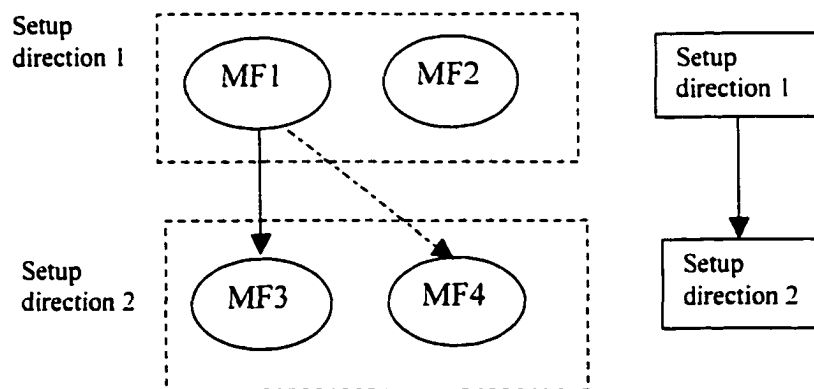


Figure 5.19(a) CASE I: unidirectional precedence constraints.

In CASE I, only the features in one setup direction have precedence over the features in the other setup direction. It is obvious in this case that the setup direction for the features having the precedence should precede the other.

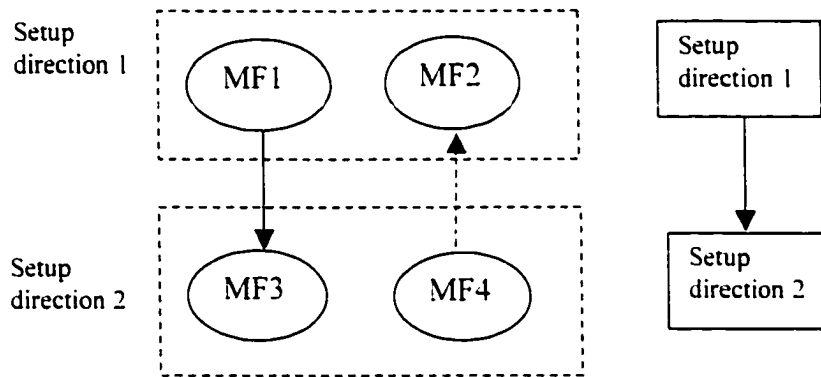


Figure 5.19(b) CASE II: bi-directional precedence constraints with different constraint types.

In CASE II, two precedence constraints, one from the capability-based rules and the other from the efficiency-based rules, conflict each other. Since the capability-based rules must be always complied, the setup direction for features having capability-based precedence constraints should precede the other.

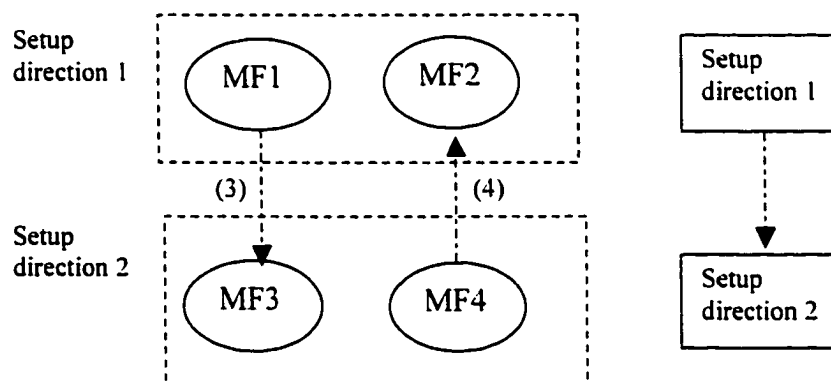


Figure 5.19(c) CASE III: bi-directional efficiency-based precedence constraints.

In CASE III, two precedence constraints also conflict each other. But in this case, both constraints are from efficiency-based machining rules. In this case, the setup direction for features having the highest priority precedes the other.

In CASE IV, two constraints, both from capability-based machining rules, conflict each other. Since neither of them can be violated, two possible sequences as shown in Figure 5.19(d) need to be considered.

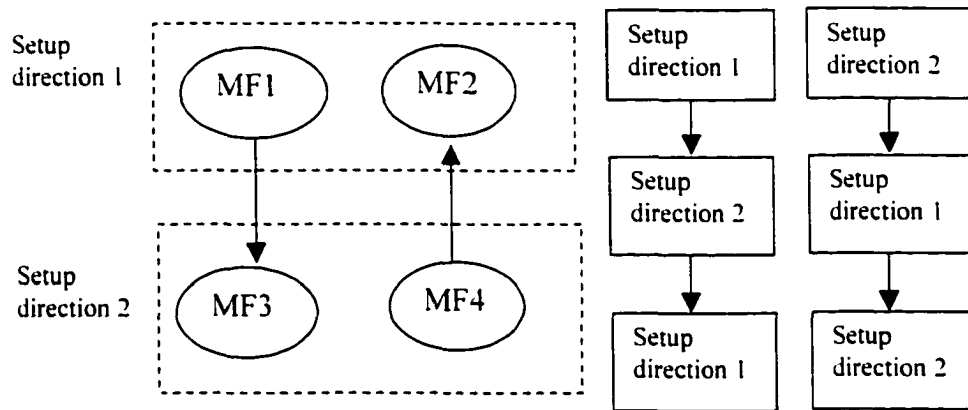


Figure 5.19(d) CASE IV: bi-directional capability-based precedence constraints.

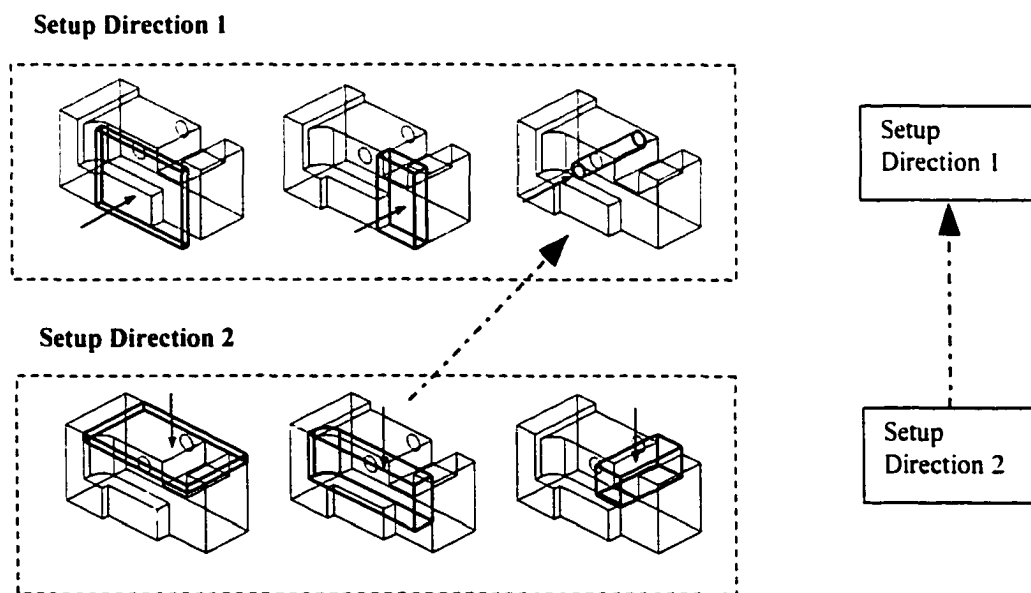


Figure 5.20 Precedence between two setup directions.

Figure 5.20 shows the sequence of the setup directions for the part in Figure 5.16. Because MF5 in setup direction 2 has the precedence over MF3 in setup direction 1, the features in setup direction 2 are machined first.

Once precedence constraints among setup directions are identified, a method similar to the process for sequencing features in a setup direction is used to sequence the setup directions. First, a PCT of the setup directions is generated, and then a setup direction having no precedence is selected first. If there are more than one such setup directions, we currently select the setup direction in which the largest number of features can be machined. This is a rule similar to the one used in sequencing the features in each setup. By machining the largest number of features, more of overlapping volumes can be removed in the setup directions. This process continues until all the setup directions are selected.

5.5.2.4 Generating Non-Overlapping Ordered Features

The overlapped volume between two features is removed during machining of either of the two features. To evaluate plans accurately, therefore, there is a need to generate non-overlapping features. The non-overlapping feature of a maximal feature is generated by subtracting from the maximal feature the maximal features preceding it in the machining sequence. This operation may change the types of features. Thus, after non-overlapping features are generated, the types of the features need to be identified.

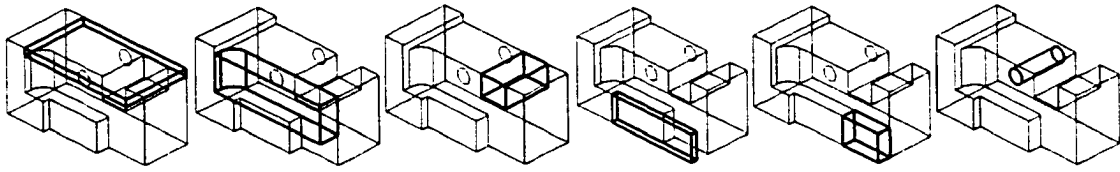


Figure 5.21 Non-overlapping ordered features for the part in Figure 5.16.

5.6 Evaluation of Plans

The method presented in the previous sections generates one or more machining sequences for a part. If the method generates only one sequence, the sequence is the optimal plan. If the method generates multiple sequences, the sequences are evaluated and the optimal one is selected. The objective function of the optimization is the machining time. Thus, we need to estimate the machining time for each sequence.

Estimation of the machining time begins with selection of cutters for features. Two cutters, one for roughing cut and the other for finishing cut, are to be used for each feature. Each cutter for machining a feature is selected from a given set of cutters so that the diameter of the selected cutter is equal to or less than the diameter calculated by the method in chapter 4.

Based on the cutter sizes and the material, parameters such as feed rates, depth of cut, and width of cut are determined by retrieving values from a machining data table. Then the length of the cutter path for each machining operation is estimated. In estimating the lengths of cutter paths, the zigzag pattern of cutter path is used for roughing cut as shown in Figure 5.22(b), and the contour parallel pattern of cutter path is used for finishing cut as shown in Figure 5.22(c).

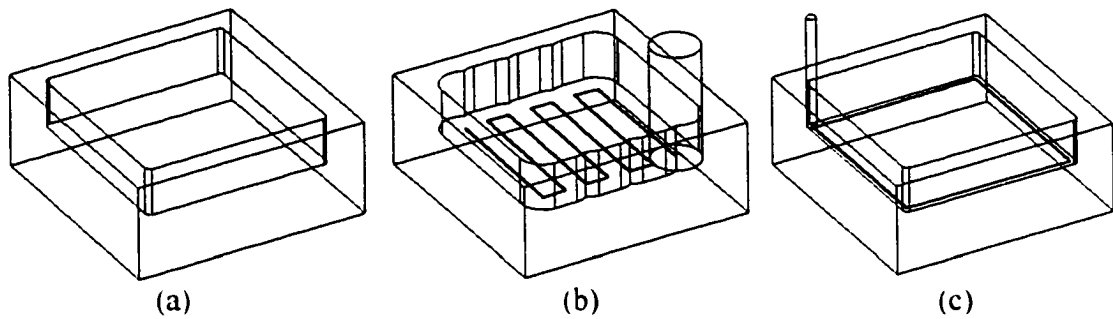


Figure 5.22 (a) A feature to be machined; (b) roughing cut; (c) finishing cut.

The time required for roughing cut for a feature, T_{r_i} , is approximated as:

$$T_{r_i} = L_r \text{ (mm) } / F_r \text{ (mm/sec) } + \alpha \text{ (sec)},$$

where L_r is the length of the cutter path for roughing cut, and F_r is the feed rate for roughing cut. α is the time required for ramping for a closed pocket. α is zero for other features. Likewise, the time required for finishing cut for a feature, T_{f_i} , is approximated as:

$$T_{f_i} = L_f \text{ (mm) } / F_f \text{ (mm/sec)},$$

where L_f is the length of the cutter path for finishing cut, and F_f is the feed rate for finishing cut.

Then, the total machining time for a plan, T , is estimated as follows:

$$T = \sum_{i=1}^n (Tr_i + Tf_i) + mT_s .$$

where Tr_i = time required for roughing cut for a feature.

Tf_i = time required for finishing cut for a feature.

T_s = time required for setup.

n = number of features to be machined in the plan, and

m = number of setups.

Chapter 6

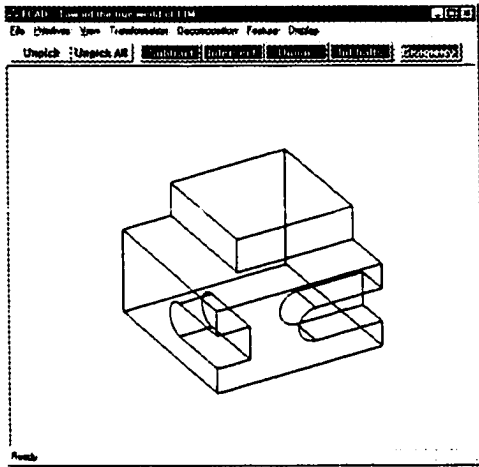
Implementation and Case Studies

6.1 Implementation

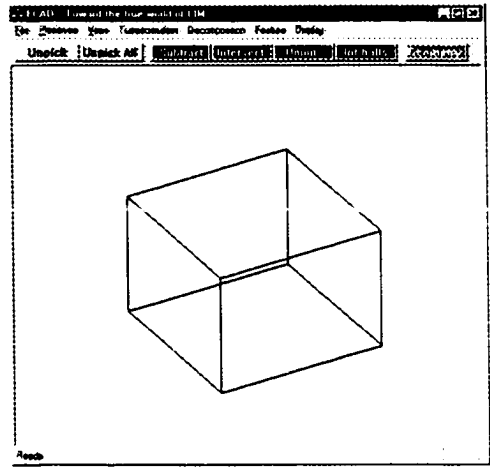
The methods presented in the previous chapters were implemented as two programs. The program for feature recognition, presented in chapter 3, was written on a Silicon Graphics Indy workstation using C with a locally developed solid modeler. And the program for plan generation, presented in chapters 4 and 5, was written on a Windows-based PC using C/C++ with the solid modeler. The programs were tested with some mechanical parts.

6.2 Case Study 1

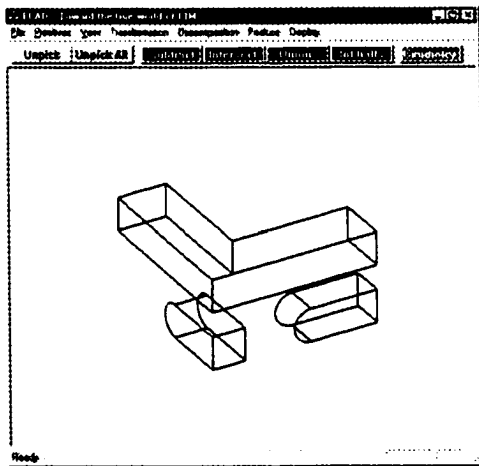
Figure 6.1(a) shows the solid model of a simple mechanical part, which was similar to the part presented in a paper on feature recognition [10]. The delta volume in Figure 6.1(c) was first generated by subtracting the part from the raw material in Figure 6.1(b). The delta volume was then decomposed into four maximal volumes in Figure 6.1(d), and all of them were recognized as maximal features. Two setups and four machining operations were required to create this part. The figures in Figure 6.2 show the plan. In each of the figures, the feature is machined from the top.



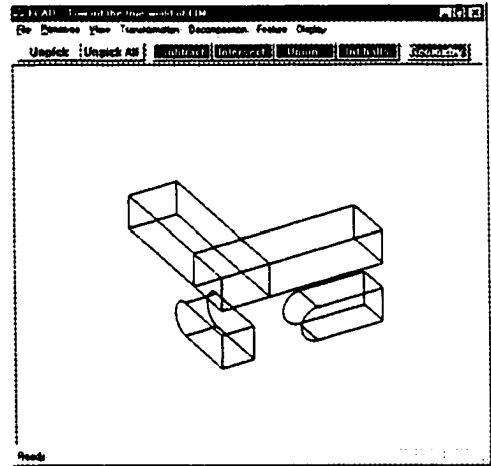
(a)



(b)



(c)



(d)

Figure 6.1 (a) part; (b) raw material; (c) delta volume; (d) maximal volumes of the delta volume.

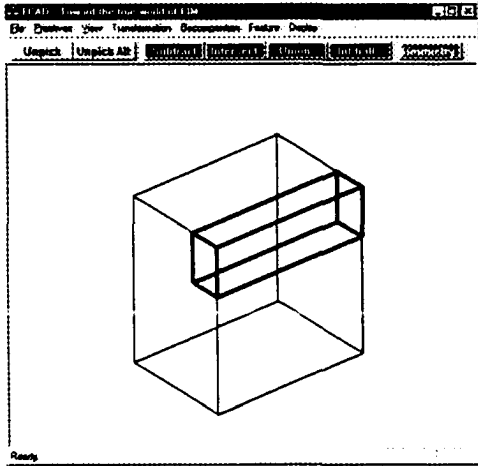


Figure 6.2(a) 1st machining operation: step.

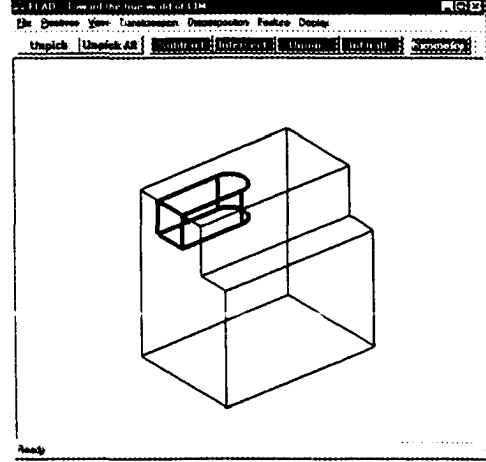


Figure 6.2(b) 2nd machining operation: blind slot.

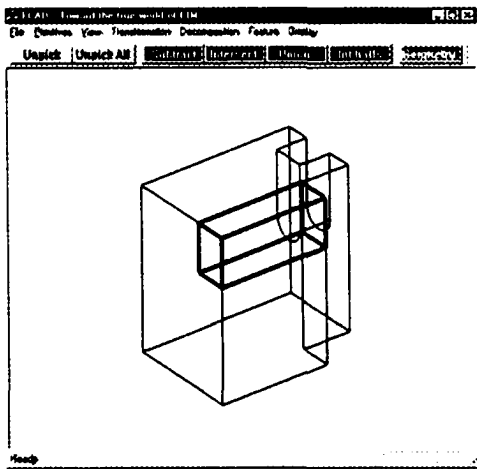


Figure 6.2(c) 3rd machining operation: step.

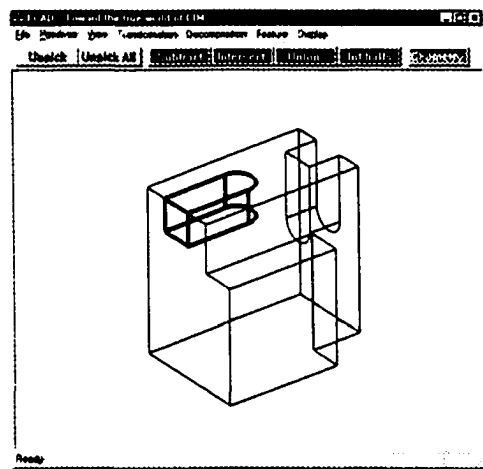


Figure 6.2(d) 4th machining operation: blind step.

6.3 Case Study 2

The part in Figure 6.3(a) is the solid model of a part similar to the part in Figure 6.1(a). The delta volume is decomposed into four maximal volumes, and all of them were recognized as maximal features. The pocket in the right side of the part is different

from that of the part in Figure 6.1(a). Because of the different setup direction for the pocket, two step features were merged into one feature. Figure 6.4 shows the process plan.

It is interesting that a slight change in a feature can result in a big change in a process plan. This capability may be utilized in design for manufacturing since a slight change in design may result in a big difference in manufacturing cost.

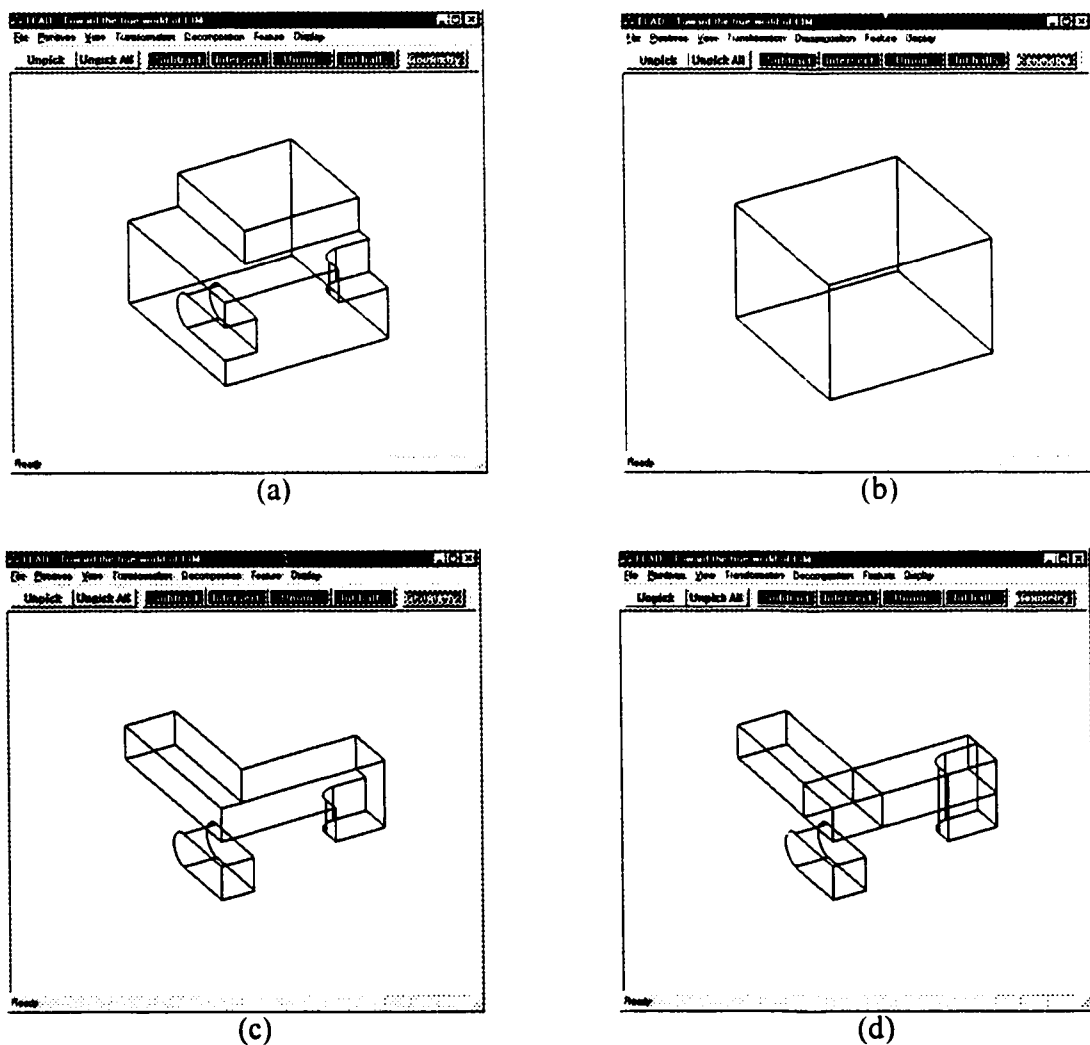


Figure 6.3 (a) a part; (b) raw material; (c) delta volume; (d) maximal volumes of the delta volume.

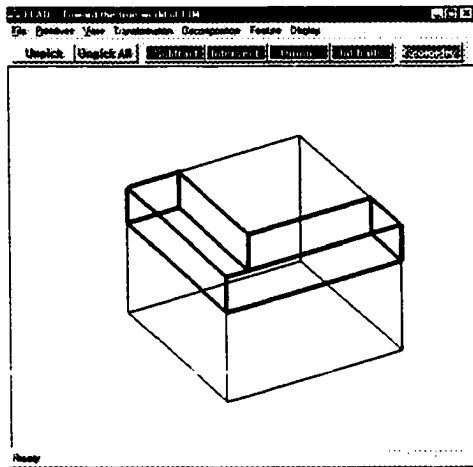


Figure 6.4(a) 1st machining operation: open pocket.

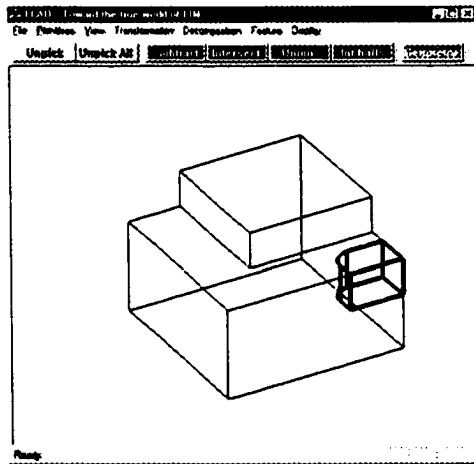


Figure 6.4(b) 2nd machining operation: open pocket.

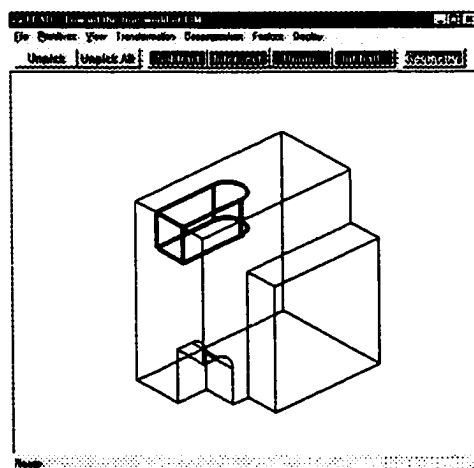


Figure 6.4(c) 3rd machining operation: blind slot.

6.4 Case Study 3

Figure 6.5(a) shows a mechanical part obtained from an aircraft seats manufacturer located in Colorado Springs, Colorado. The part is one of the most complex parts we tested. The delta volume was decomposed into 24 maximal volumes, and 22 maximal features were recognized from the maximal volumes. For the features, there were five possible setup directions, from which two S_D 's having two setup directions were selected. Two plans generated from two SFMs were evaluated. In each

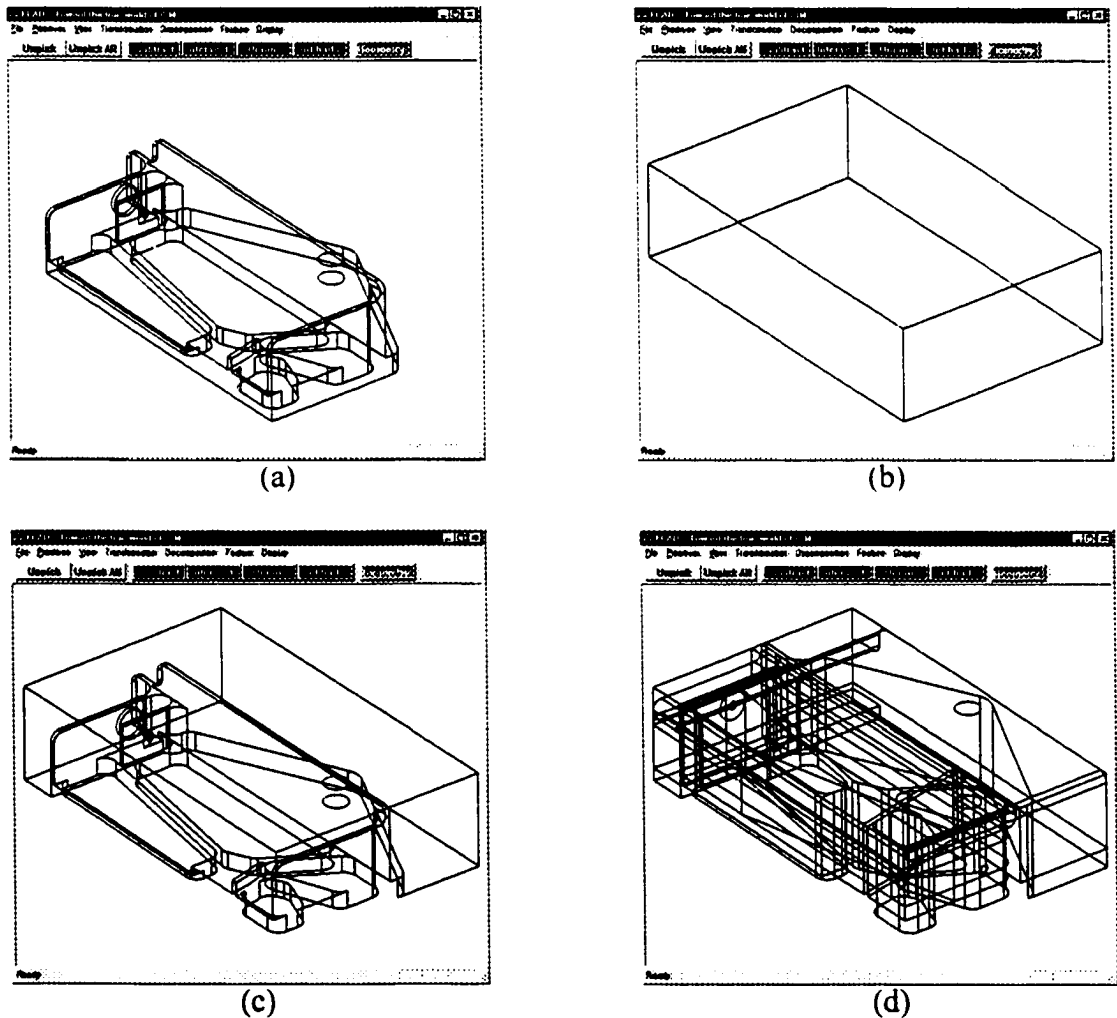


Figure 6.5 (a) a part; (b) raw material; (c) delta volume; (d) maximal volumes of the delta volume.

of the SFMs, three maximal features were merged into one feature. The optimal plan for this plan requires four setups and 20 machining operations. The estimated time required for machining the part is 52.3 minutes. The plan is shown in Figures 6.6(a) to 6.6(t).

We visited the company and interviewed a machinist regarding the goodness of this process plan. According to the interview, this process plan is satisfactory and can provide useful information necessary for complete process planning. But for better optimization, more parameters than we considered such as number of tool changes need to be incorporated.

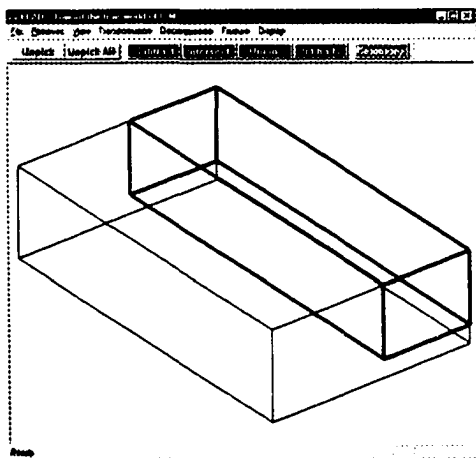


Figure 6.6(a) 1st machining operation: step.

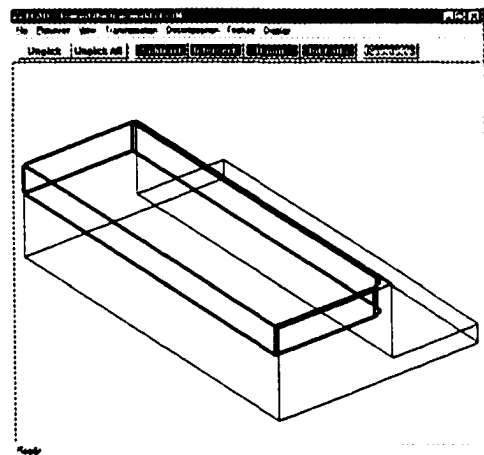


Figure 6.6(b) 2nd machining operation: open pocket.

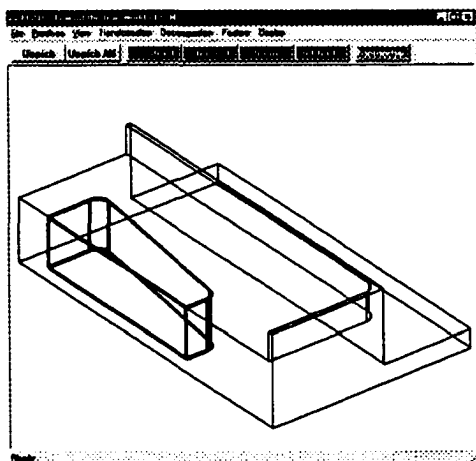


Figure 6.6(c) 3rd machining operation: open pocket.

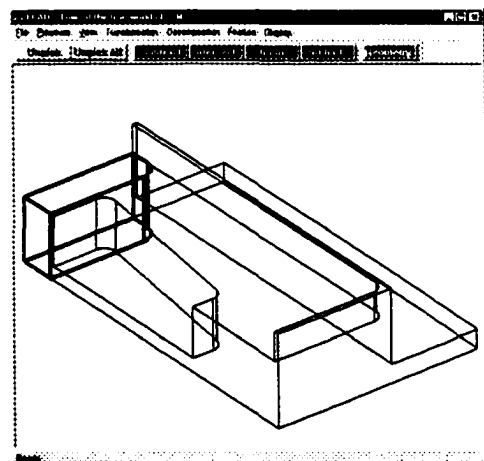


Figure 6.6(d) 4th machining operation: profile.

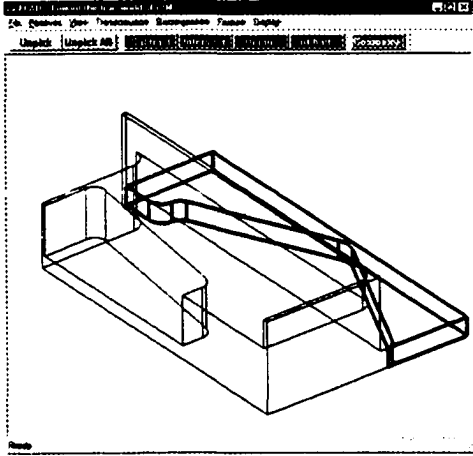


Figure 6.6(e) 5th machining operation: profile.

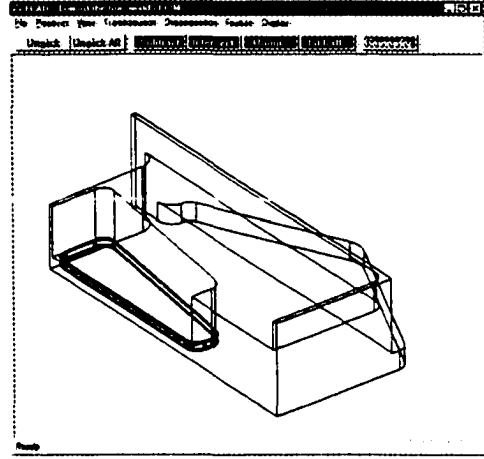


Figure 6.6(f) 6th machining operation: closed pocket.

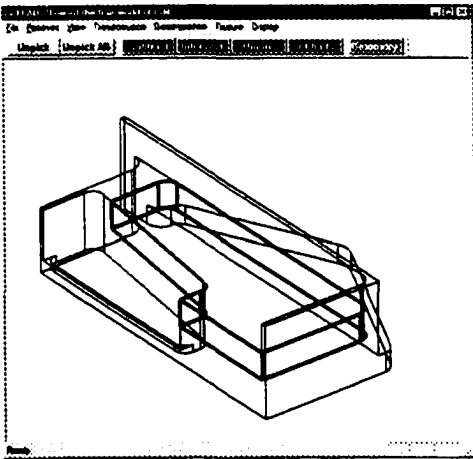


Figure 6.6(g) 7th machining operation: open pocket.

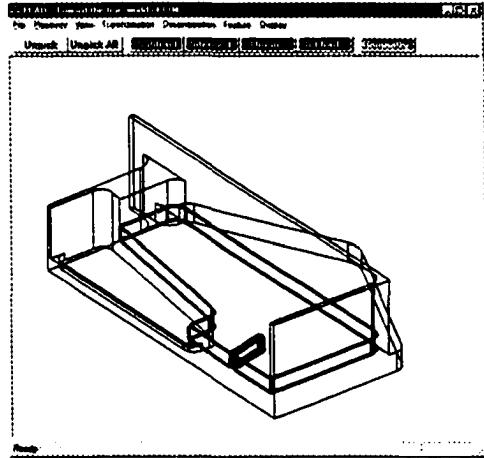


Figure 6.6(h) 8th machining operation: open pocket.

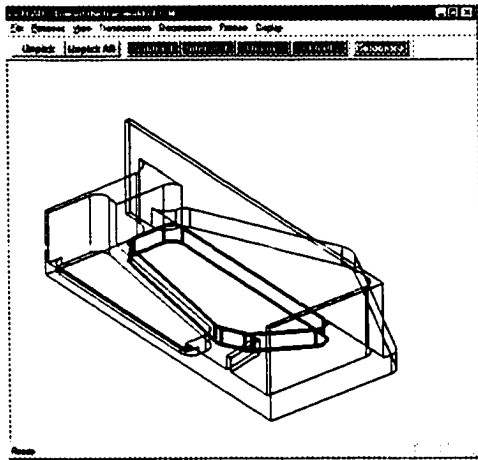


Figure 6.6(i) 9th machining operation: closed pocket.

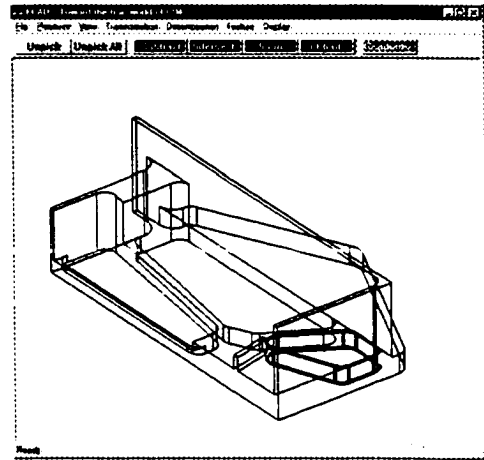


Figure 6.6(j) 10th machining operation: closed pocket.

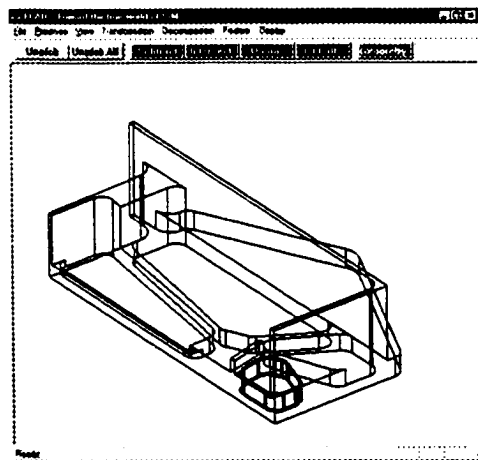


Figure 6.6(k) 11th machining operation: closed pocket.

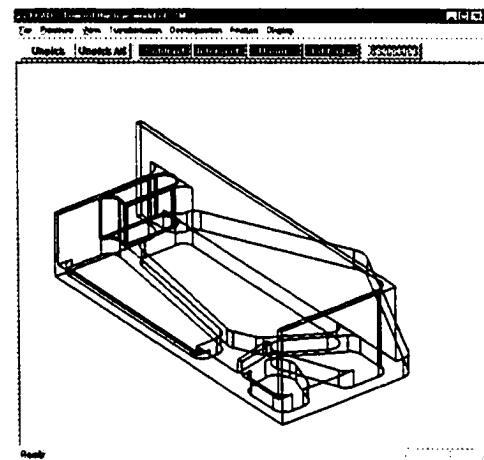


Figure 6.6(l) 12th machining operation: open pocket.

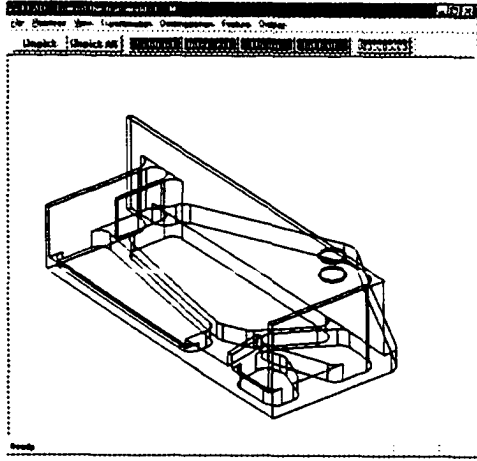


Figure 6.6(m) 13th machining operation: through hole.

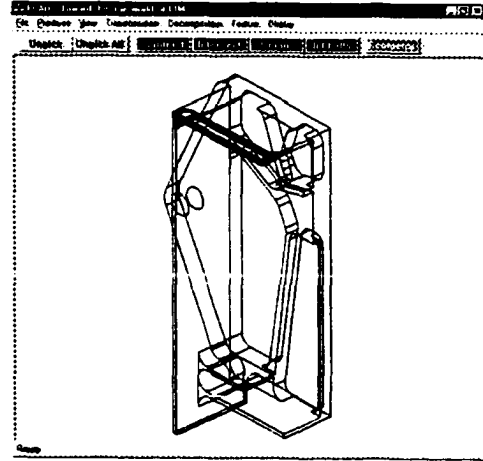


Figure 6.6(n) 14th machining operation: profile.

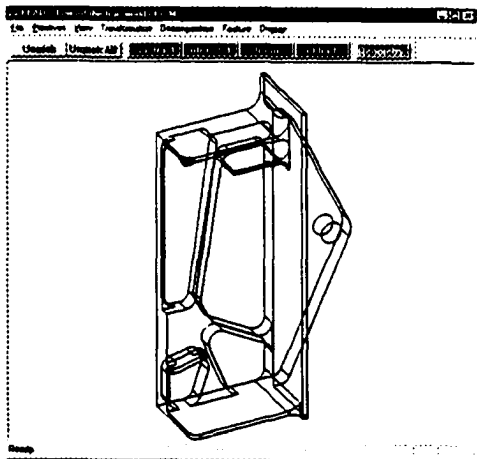


Figure 6.6(o) 15th machining operation: round.

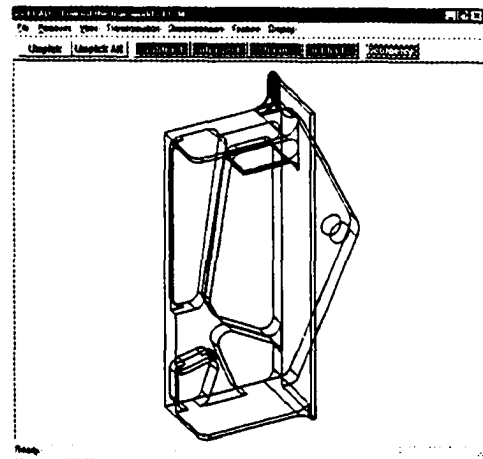


Figure 6.6(p) 16th machining operation: step.

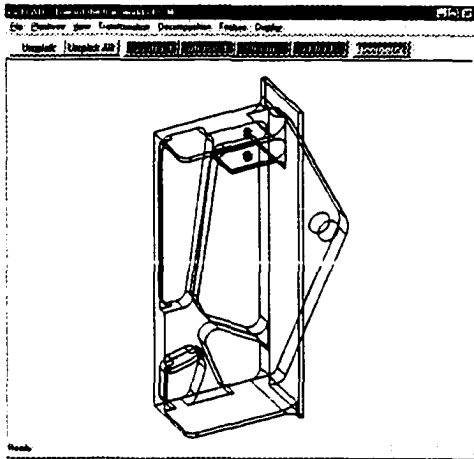


Figure 6.6(q) 17th machining operation: through hole.

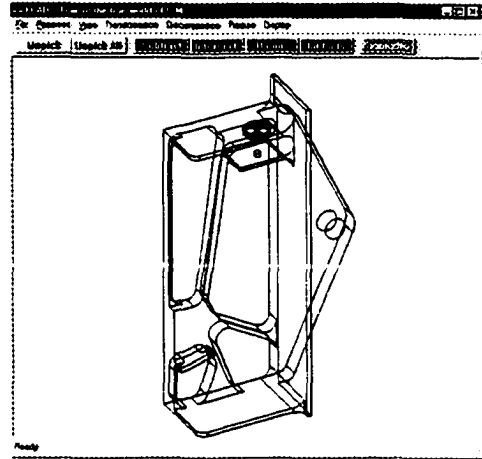


Figure 6.6(r) 18th machining operation: through hole.

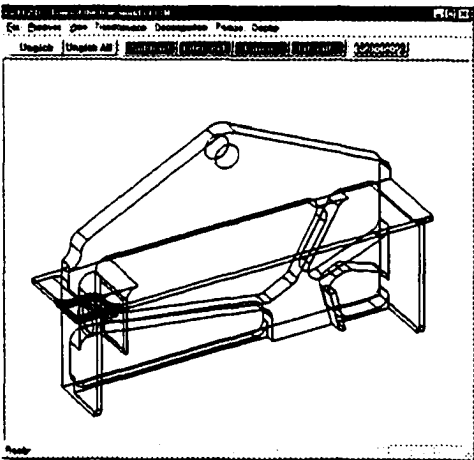


Figure 6.6(s) 19th machining operation: profile.

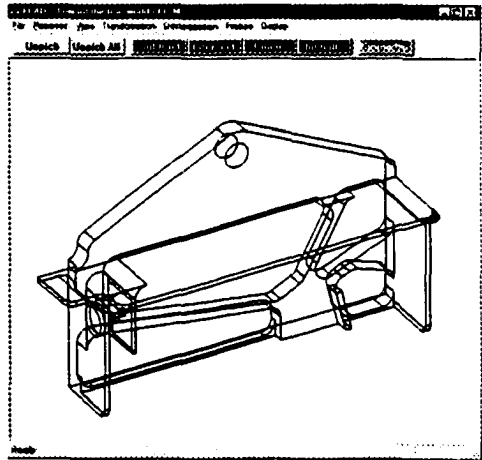


Figure 6.6(t) 20th machining operation: round.

6.5 Case Study 4

This part was taken from the web site (<http://www.mel.nist.gov/pptb>) prepared by National Institute of Standard and Technology (NIST) for the public use in research. The delta volume shown in Figure 6.7(c) was decomposed into 33 maximal volumes as shown in Figure 6.7(d), and 22 maximal features were recognized from them. From the maximal features, one SFM was generated and eight maximal features in the SFM were merged into two features. Two setups and 16 machining operations were required for machining this part. The estimated time needed to machine this part was 83.0 minutes.

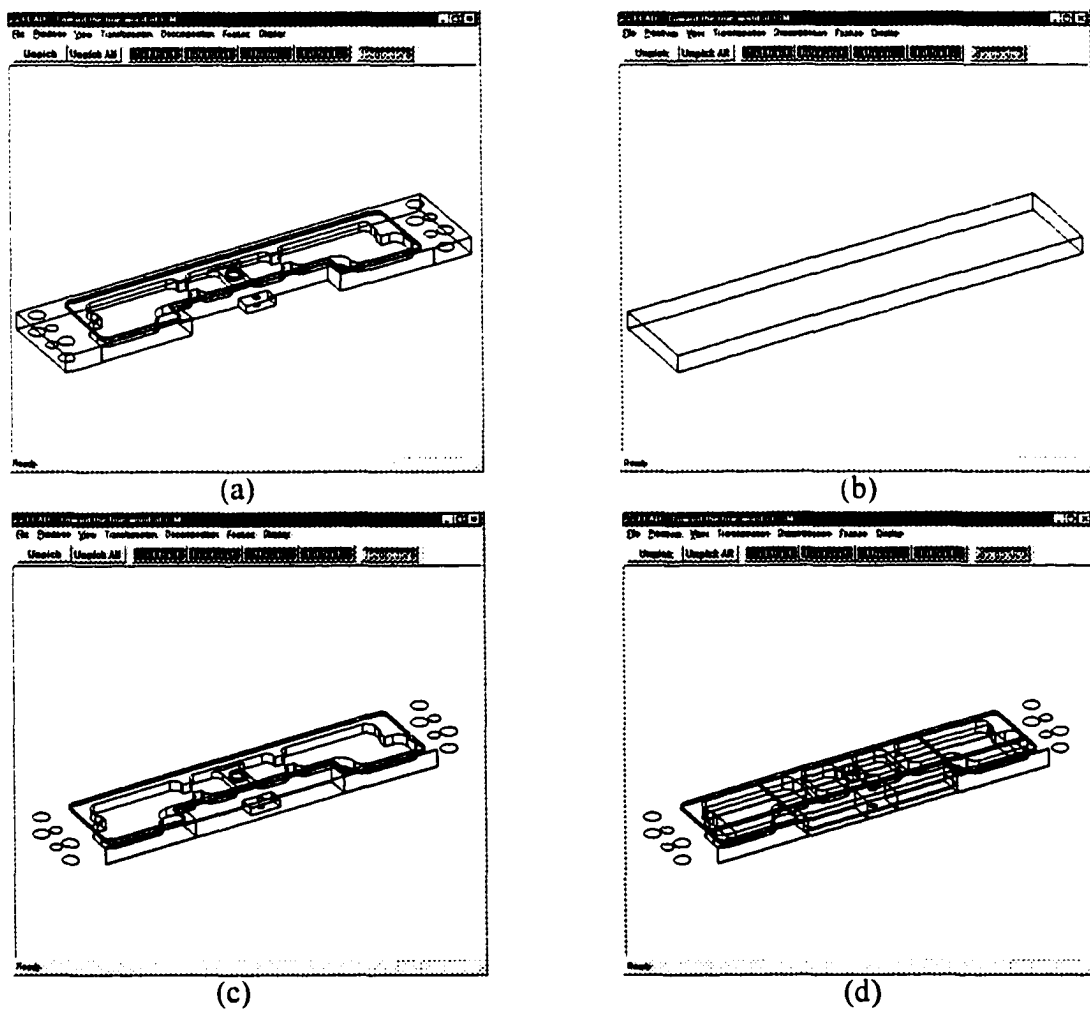


Figure 6.7 (a) a part; (b) raw material; (c) delta volume; (d) maximal volumes of the delta volume.

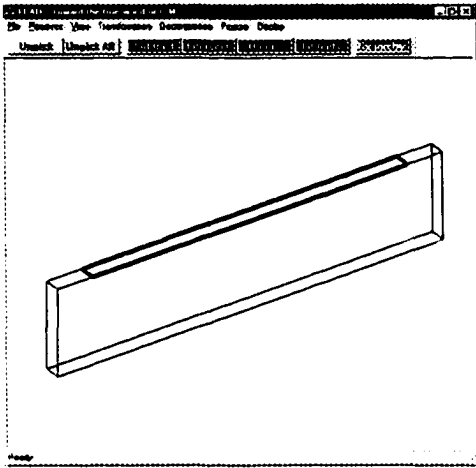


Figure 6.8 (a) 1st machining operation: step.

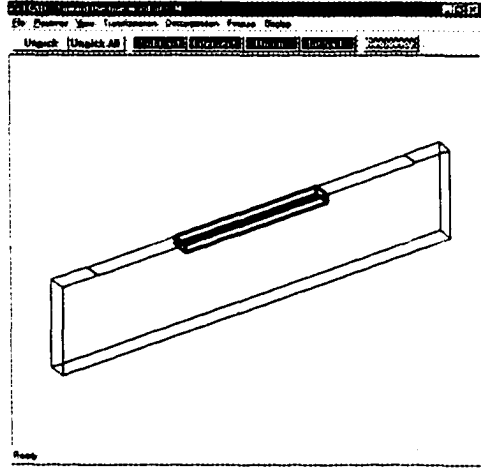


Figure 6.8 (b) 2nd machining operation: step.

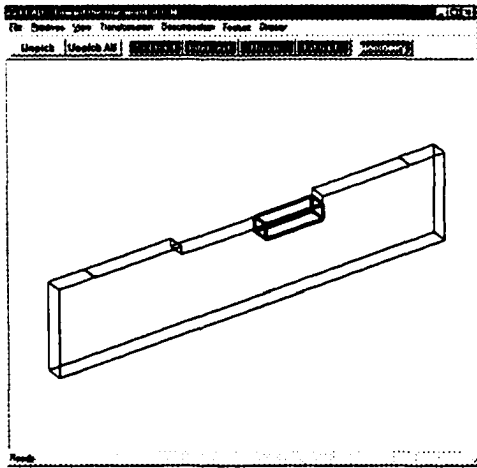


Figure 6.8 (c) 3th machining operation: step.

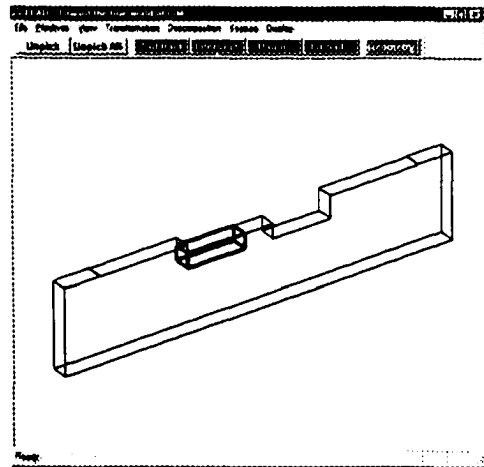


Figure 6.8 (d) 4th machining operation: step.

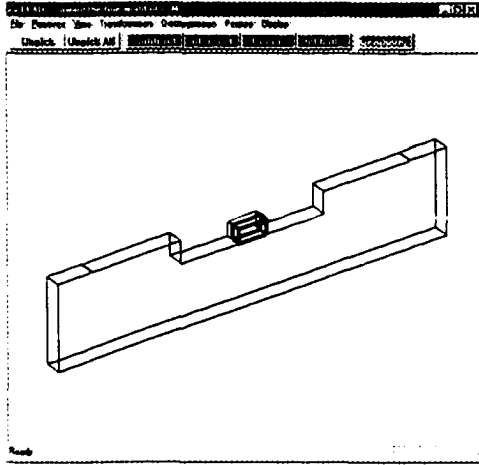


Figure 6.12 (e) 5th machining operation: open pocket.

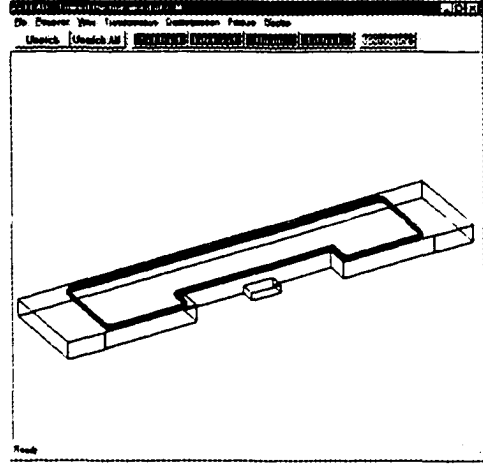


Figure 6.8 (f) 6th machining operation: closed pocket.

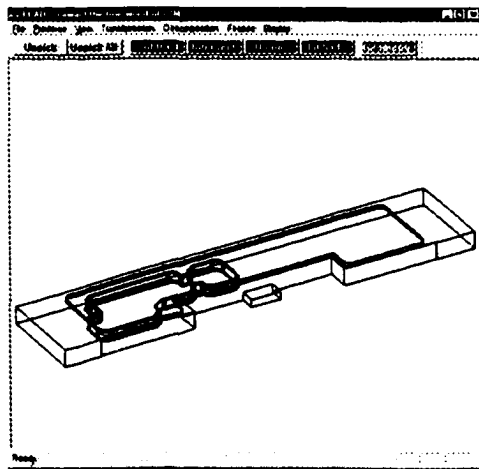


Figure 6.8(g) 7th machining operation: closed pocket.

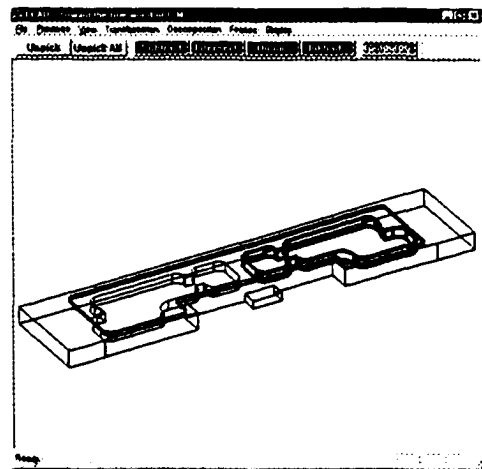


Figure 6.8(h) 8th machining operation: closed pocket.

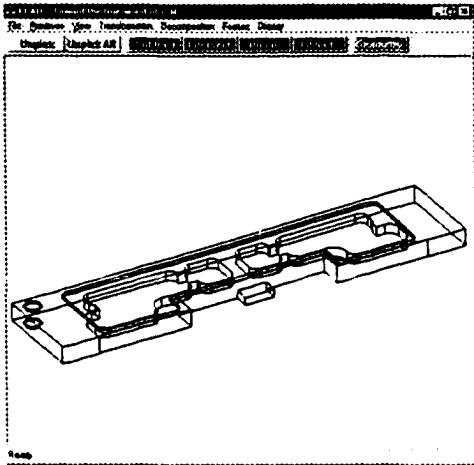


Figure 6.8 (i) 9th machining operation: through hole.

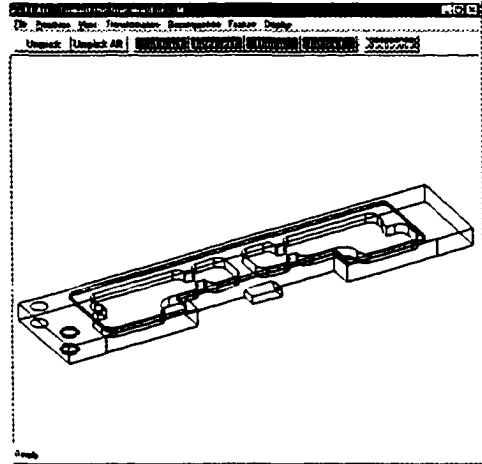


Figure 6.8(j) 10th machining operation: through hole.

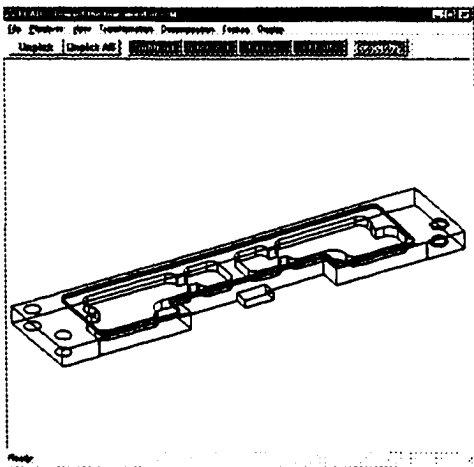


Figure 6.8(k) 11th machining operation: through hole.

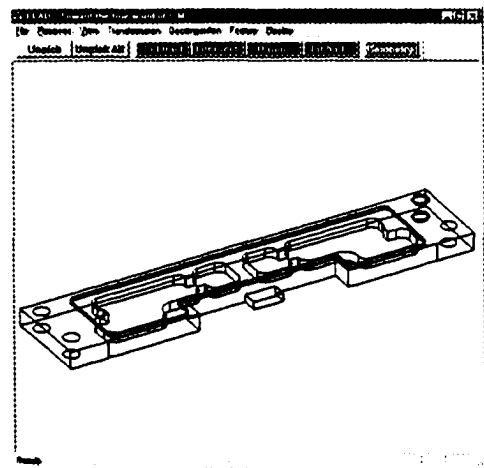


Figure 6.8(l) 12th machining operation: through hole.

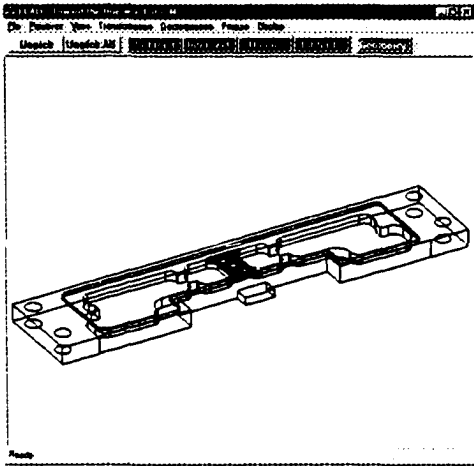


Figure 6.8(m) 13th machining operation: open pocket.

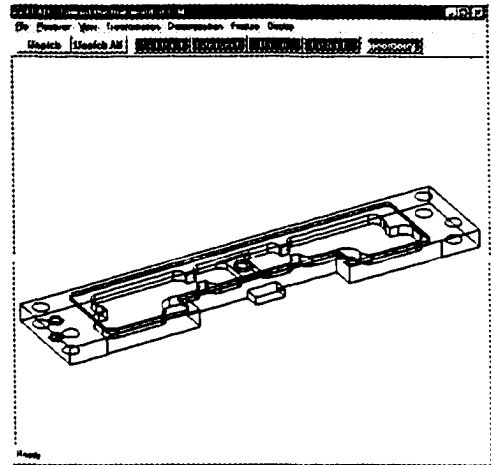


Figure 6.8(n) 14th machining operation: through hole.

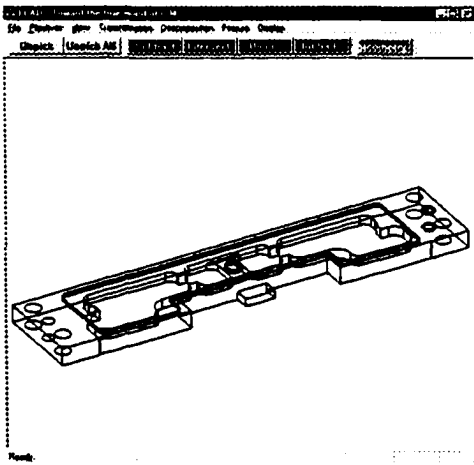


Figure 6.8(o) 15th machining operation: through hole.

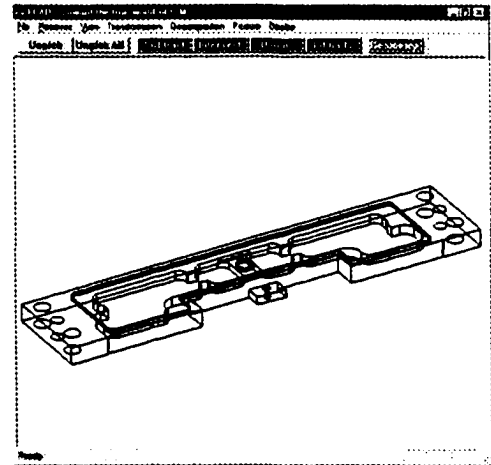


Figure 6.8(p) 16th machining operation: through hole.

Chapter 7

Conclusions

7.1 Contributions

The main contributions of this research are summarized as follows:

1) **Recognition of the optimal machining features**

Machining features to be recognized are not unique. To generate the optimal process plans, it is essential to recognize the optimal machining features. This research presented a systematic method to recognize the optimal machining features and their machining sequence by actually performing process planning.

2) **Improvement of the scalability of feature recognition**

The scalability of a feature recognition algorithm is crucial for the algorithm to be used for complex industrial parts. Existing algorithms that can recognize intersecting features are so slow that they often do not recognize features within any practical length of time. The feature recognition method by recursive volume decomposition developed in this research improved the scalability significantly.

3) **Optimization of machining parameters**

Optimization of machining parameters is essential not only for automating process

planning but also for optimizing NC programs. Among many machining parameters, setup directions and cutter diameters are two important factors that affect the quality of a process plan. Machining parameters such as feed rate, speed, and depth of cut depend on the setup directions and the cutter diameters. This research presented a method to determine the minimum number of setup directions and to find maximum cutter sizes for roughing and finishing operations.

4) Demonstration of feasibility of CAD/CAM integration

Automation of process planning has been a major missing link in achieving CAD/CAM integration. By successfully generating optimal process plans, this research showed that CAD/CAM integration is a difficult but achievable task. It is believed that this research provides the stepping stone for future research on CAD/CAM integration.

7.2 Future Work

The followings are some of the recommendations for future work to achieve a more robust and practical system of automatic process planning.

1) Improving the optimization method

The optimization method needs be improved in two aspects. First, more factors such as number of tool changes and capabilities of machines need to be considered in generating the optimal process plan. Second, the method for automatic generation of the optimal process plans must be not only complete but also efficient. The

completeness sometimes needs to be sacrificed to improve the efficiency. However, this must be done without jeopardizing the goodness of the plans. In order to develop a practical process planning system, the optimization method needs to be improved so that it can balance this trade-off.

2) Developing interface for human intervention.

Since some tasks in process planning are extremely difficult to automate, it is suspected that human interventions are indispensable for such tasks. For example, fixture design is a crucial but a very difficult task to automate. Therefore, human intervention will be an integral component of CAD/CAM integration for a long time in future. It is necessary to address how to build an effective and powerful interface for human intervention to extend CAD/CAM integration.

3) More accurate estimation of machining time

The method to estimate the machining time for a process plan has been developed with several approximations. To get more realistic estimations, the method needs to be improved by using more accurate approximation of the lengths of cutter paths or incorporating auxiliary time such as tool change time.

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