To deal with the overlapping activities, the following actions can be taken:

- One may view the overlapping activities as a server that control the other six groups of activities (clients).
- One may replace an overlapping activity with an alternative activity that involves different inputs/outputs.

5 CONCLUSION

The concurrency analysis improves the design process based on the process flow; while, the critical analysis is based on the process structure. The purpose of the two approaches is the same; i.e., improvement of the design process without the availability of detailed information. The two approaches complement each other. The decomposition approach identifies groups of activities with minimum interdependencies between them.

The future research is to develop a knowledge-based system employing a domain-specific knowledge to analyze the design process based on different types of dependencies between design activities. Some dependencies may be removed by redefining design activities or adding more resources. Another extension is to adapt the concurrency and critical analysis to monitor the project, as design process proceeds.

ACKNOWLEDGMENT

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APPENDIX: ACTIVITIES INCLUDED IN PHASE 3 OF THE DESIGN PROCESS

1. Update Rtm assessment
2. Develop engineering test equipment concepts/plans
3. Develop program PPSL
4. Order/receive engineering
5. Supportability analysis
6. Update LSAR
7. Update MTBF/MTTR
8. Design/Select components (HW)
9. Provide parts technology guidance
10. Support component selection/testing
11. Produce S/W specifications (SYS/SW)
12. SRU level block diagram (HW)
13. Cost update against cost goals
14. Breadboard test/equipment design
15. Module specifications (HW)
16. Create interface specifications
17. Develop package specifications (SW)
18. Order breadboard test/equipment parts
19. Procure samples (D, E)
20. Walkthrough/review package specifications (SYS, SW)
21. Review SRS
22. Order/review breadboard parts
23. SWE review IRS
24. Release SRS
25. Approve SRS (Procedure 2)
26. Approve SRS (Procedure 1)
27. Review SRS
28. Receive SRS approval

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INTERPRETING PRODUCT DESIGNS FOR MANUFACTURABILITY EVALUATION

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ABSTRACT

The ability to quickly introduce new quality products is a decisive factor in capturing market share. Because of pressing demands to reduce lead time, analyzing the manufacturability of the proposed design has become an important step in the design stage. This paper presents an approach for evaluating the manufacturability of machined parts.

Evaluating the manufacturability of a proposed design involves estimating the production cost and quality associated with manufacturing it. Since there can be several different ways to manufacture a proposed design, this requires us to consider different ways to manufacture it, in order to determine which one best meets the manufacturing objectives.

In this paper we describe a methodology for systematically generating and evaluating alternative operation plans. As a first step, we identify all machining operations which can potentially be used to create the given design. Using these operations, we generate different operation plans for machining the part. Each time we generate a new operation plan, we assign it a manufacturability rating. The manufacturability rating for the design is the rating of the best operation plan.

We anticipate that by providing feedback about possible problems with the design, this work will help in speeding up the evaluation of new product designs in order to decide how or whether to manufacture them.

1. INTRODUCTION

In today's competitive market, the ability to quickly introduce new quality products is a decisive factor in capturing market share. Because of pressing demands to reduce lead time, the traditional approach to product development is being replaced with the concept of design for manufacturability. This involves identifying and alleviating manufacturing problems while the product is being designed, and thereby reducing the lead time. One way to support this activity is by providing tools that automatically evaluate the manufacturability of a proposed design as it is being developed. We are developing such tools, for use in evaluating the manufacturability of machined parts.

Evaluating manufacturability involves finding a way to manufacture the proposed design and estimating the associated production cost and quality. However, there often can be several different ways to manufacture a proposed design—and the manufacturability of the given part should be associated with the best available plan to manufacture the part. Thus, to evaluate the manufacturability of the proposed design, we need to consider different ways to manufacture a proposed design, to determine which one is best.

We have developed a methodology for systematically generating and evaluating alternative operation plans, to see which ones best balance quality against cost. As illustrated in Fig. 1, the basic idea is to generate alternative interpretations of the part as collections of machinable features, map these interpretations into operation plans, and evaluate the manufacturability of each operation plans. This paper focuses mainly on the generation of the alternative interpretations and operation plans; our work on manufacturability evaluation is described in [1]. Because of space limitations, we have avoided presenting detailed description of our algorithms; instead, this paper attempts to explain the basic ideas through simple examples.

We expect that the information provided by our approach will be useful in providing feedback to the designer about possible problems that may arise in trying to meet the specified geometry and tolerances. We hope this will allow the designers to correct the manufacturing problems during the design stage, and thereby produce the designs which will be easier to manufacture.

Step 1. If the part cannot be machined with the available set of machining operations, then exit, returning failure. Otherwise, build the set of all potential machining features $\mathcal{F}$ by identifying various features which can be used to create the part P from the stock S, as described in Section 4. Each feature in $\mathcal{F}$ represents a different possible machining operation which can be used to create various surfaces of the part.

Step 2. Generate a promising FBM F from the feature set $\mathcal{F}$, as described in Section 5. As described in Section 3, an FBM is basically a set of machining features that contains no redundant features and is sufficient to create the part P. We consider an FBM unpromising if it is not expected to result in any operation plans better than the ones which has already been examined.

Step 3. Generate and evaluate alternative operation plans for the features in F, by means of the following steps:

(a) Generate a promising operation plan O from F as described in Section 6. O represents a partially ordered set of machining operations. We consider an operation plan to be unpromising if it violates any common machining practices.

(b) Estimate the achievable machining accuracy of the operation plan O, as described in Section 7.1. If the operation plan O cannot produce the required design tolerances and surface finishes, then discard it and go to Step (a).

(c) Estimate the production time and cost associated with operation plan O, as described in Section 7.2.

(d) Calculate the manufacturability rating M_R of the operation plan O, as described in Section 7.3.

(e) If we have not yet examined every promising operation plan resulting from F, then go to Step (a). Otherwise, proceed to Step 4.

Step 4. If not every FBM of $\mathcal{F}$ has been considered, then go to Step 2 in order to generate the next alternative. Otherwise, return the best of the M_R values that was found in Step (d).

Figure 1: Basic approach for manufacturability evaluation of machined parts.

2. REVIEW OF PREVIOUS RESEARCH

Because of the recent popularity of feature-based approaches in a variety of CAD/CAM systems, a vast amount of literature refers to features in one way or another, but different researchers use the term *feature* to mean different things. Significant amounts of research have been directed towards developing a set of features to serve as communication medium between the design and manufacturing domains [2, 3].

There are three primary approaches for obtaining features from a CAD model. In *human-supervised feature recognition*, a human user examines an existing CAD model to determine what are the manufacturing features. In *automatic feature recognition*, the same feature recognition task is performed by a computer system [4, 5, 6]. In *design by features*, the designer specifies the initial CAD model in terms of various form features which translate directly into the relevant manufacturing features [3]. However, each of these approaches typically produces a single set of features describing the CAD model, rather than several alternative interpretations of the model.

The AMPS process planning system [7] includes a step called "feature refinement," which consists of heuristic techniques for combining a set of features into a more complex feature if it appears that this will optimize the plan, or splitting a feature that cannot be machined into two or more features that can (hopefully) be machined. Since the techniques are heuristic in nature, it is not entirely clear when alternative interpretations will be produced.

Vandenbrande [6] has developed a system that combines techniques from artificial intelligence and solid modeling. The program uses hints or clues to identify potential features in the boundary representation of the part. The system is capable of identifying interacting features (e.g., two intersecting slots). This program also produces alternative feature interpretations in certain cases. But since there is no formalization available regarding the kinds of interactions it handles, it is hard to determine what all the interpretations it produces are.

The first systematic work in the direction of generation of alternative interpretations was done by Karinthi and Nau [8]. They describes an approach for producing alternative interpretations of the same object as different collections of machining features as the result of algebraic operations on the features, and a system for generating alternative interpretations by performing these algebraic operations. This system works with abstract volumetric features. There is no direct relation between these features and machining operations. Therefore some of the interpretations generated by this approach are not feasible from the machining point of view. In this approach a set of algebraic operators (such as maximal extension, truncation etc.) has been used to generate new interpretations of the part. But this set of operators is not sufficient to generate all interpretations of the part. Moreover, many times the resulting features do not belong to any of the feature classes. Some of the feature interactions may also result in partial ordering among features, which is an important issue from a machining point of view—but this work does not deal with time orderings among the features.

Because of the need for quality assurance on the shop floor, extensive research has been done on different aspects of evaluation of operation plans. Much of the data relevant for machining operation planning is available in machining data handbooks such as [9]. In addition, mechanistic models have been developed to provide quantitative mappings between machining parameters (such as cutting speed, feed, and depth of cut), to the performance measures of interest (such as surface finish and dimensional accuracy) [1, 7, 10, 11, 12]. Research on machining economics has produced quantitative models for evaluating time and costs related to machining operations [13, 14, 15]. Researchers have developed several different approaches to evaluate manufacturability of a given design [5, 16, 17, 18]. These approaches have been developed for wide variety of application domain and vary considerably in their sophistication.

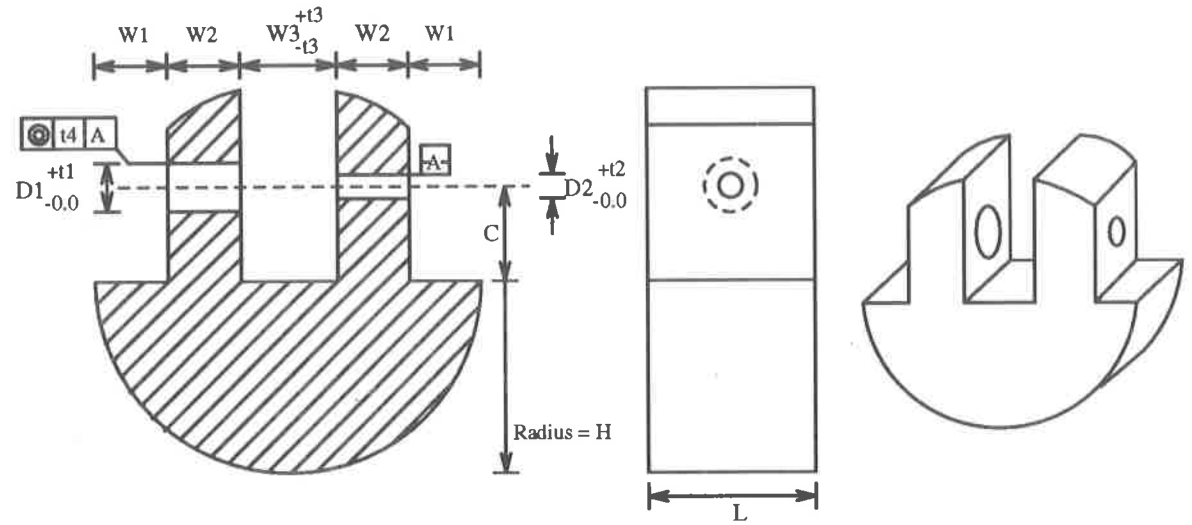


Figure 2: An example part.

Table 1: Design parameters for the part shown in Fig. 2 (all dimensions are in mm).

case	H	L	C	W1	W2	W3	D1	D2	t1	t2	t3	t4
Design 1	50	50	25	15	15	40	30	20	0.25	0.25	0.15	0.25
Design 2	50	50	25	15	15	40	15	10	0.25	0.25	0.15	0.50

3. BACKGROUND

3.1. Preliminary Definitions

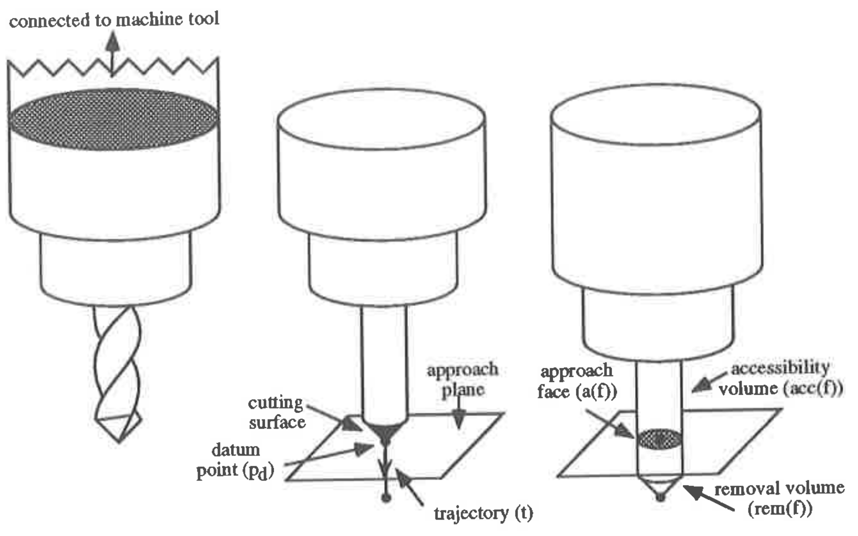
For our purposes, a *solid* is any regular, semi-analytic subset of three-dimensional Euclidean space. If R is any solid, then $b(R)$ is the *boundary* of R, and $\iota(R)$ is the *interior* of R. Note that $R = \iota(R) \cup b(R)$ and that $\iota(R) \cap b(R) = \emptyset$. A *patch* of R is a regular, semi-analytic subset of the boundary $b(R)$. If R and R' are solids, then $R \cap^* R'$ is the *regularized intersection* of a and b, i.e., the closure of $\iota(R) \cap \iota(R')$. Similarly, $R \cup^* R'$ and $R -^* R'$ are the *regularized union* and *regularized difference*, respectively.

A *part* is the finished component to be produced as a result of a set of machining operations on a piece of *stock*, i.e., the raw material from which the part is to be machined. We will represent both the part and the stock as geometric solids. Throughout this paper, we let P be a solid representing a part, and S be a solid representing the stock from which P is to be made.

Example. Consider the part shown in Fig. 2. Let us assume that this part will be machined from a cylindrical stock of radius H and length L. Suppose the part material is plain carbon steel (100 BHN). Let Design 1 and Design 2 be two different instances of the design, produced by assigning different values to the parameters, as shown in Table 1. We will analyze the manufacturability of these two designs in Section 7.

3.2. Machining Features

In a machining operation, material is removed by relative motion between the cutting tool and the workpiece. The cutting tool is mounted on a large machine tool, and the total volume occupied by the cutting tool and the machine tool is quite large. But we will only be interested in some small portion of this total volume, namely the portion that actually gets close to the workpiece. We will call this portion the *tool volume*, and we will denote it by T. Fig. 3(a) shows a drilling tool. To perform a cutting operation, the tool volume T is given a relative cutting motion with respect to the workpiece. This cutting motion may either be imparted to the tool (examples include various milling operations) or the workpiece (examples include various lathe operations). Most of the time this relative cutting motion is either linear (operations such as shaping, planning, broaching) or rotational (operations such as turning, drilling, boring, milling). We represent this motion as a sweep s_v which is either linear or rotational. Let T_v denote the solid generated by applying sweep s_v to the solid T. For the purpose of locating the



(a) drilling tool (T) (b) T after rotational sweep (T_v) (c) tool swept volume (T_{sv})

Figure 3: A drilling tool, and the resulting swept volume.

tool, we choose a particular point p_d of T_v as a *datum point.* Fig. 3(b) shows T_v and p_d for drilling operations.

For our purposes, a *machining feature* is the portion of the workpiece affected by a machining operation. However, we will need to know not just the volume of material which the feature can remove from the workpiece, but also what kind of machining operation we are performing, and how we access the workpiece in order to perform the operation. More formally, a machining feature is a triple

$$f = (rem(f), acc(f), class(f)),$$

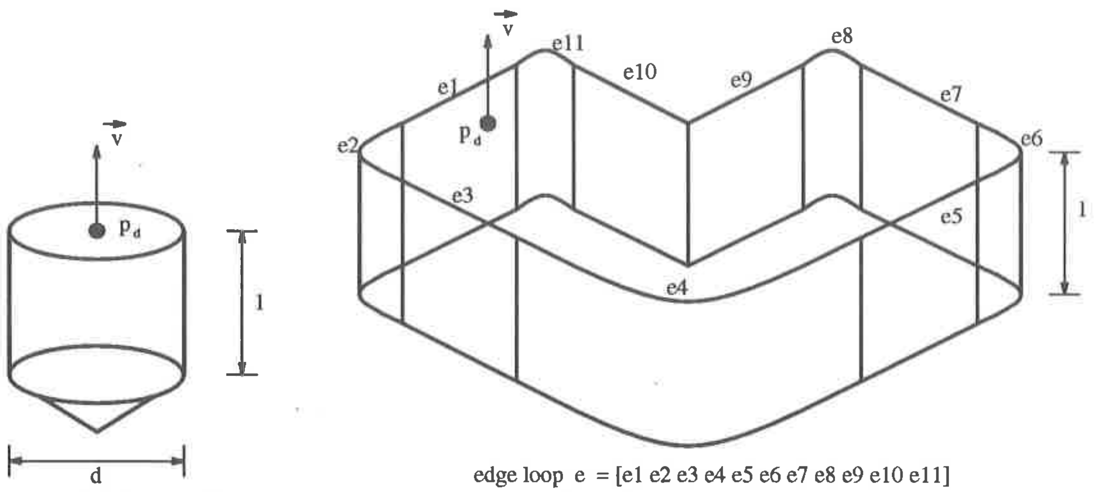
where $rem(f)$, $acc(f)$, and $class(f)$ are as defined below:

- To perform the machining operation, one sweeps the volume T_v along some trajectory t. Given a volume T_v and a workpiece W, the trajectory t is *feasible* for T_v and W only if sweeping T_v along t does not cause interference problems between the non-cutting surface of T_v and the workpiece. Fig. 3(b) shows an example of a feasible tool trajectory for drilling. If t is feasible, then the solid created by sweeping T_v is $T_{sv} = \{(p - p_d) + q : p \in T \text{ and } q \in t\}$, as shown in Fig. 3(c). However, only a portion of T_{sv} actually corresponds to the volume that can be removed by the machining feature.

  Let the *approach surface* π be a surface touching solid T_v and containing T_v to one of its sides. This surface is either a plane or a cylinder depending upon the machining operation. For drilling operations this surface is planar as shown in Fig. 3(b). The side containing T_v is called accessibility side. The other side is called removal side. The *approach face* of f is defined as $a(f) = \pi \cap^* T_{sv}$. The *removal volume* of f is the solid $rem(f)$ consisting of all points in T_{sv} that are on the removal side of π.
- The *accessibility volume* for f is the solid $acc(f)$ consisting of all points in T_{sv} that are on the accessibility side of π.
- The feature f will be an *instance* of some *feature class* ϕ, which is a parameterized set of machining features characterized by the shape and trajectory of the cutting tool. If f is a feature in ϕ, then the *class* of f is $class(f) = \phi$. If f is an instance of ϕ, then the f's *parameters* in ϕ are the specific set of parameter values for ϕ that yield f. Below are two examples:
  - If we are interested in drilling holes, then we may define ϕ_h to be the set of all features that can be created by sweeping a drilling tool of diameter d along a linear trajectory starting at the datum point p_d and going in along some unit vector $\vec{v}$ for some distance l. Thus, we can specify a particular feature in ϕ_h by giving specific values for p_d, $\vec{v}$, d, and l.
  - If we are interested in making end milled pockets or slots, then we may define ϕ_e to be the set of all features that can be created by sweeping an end mill of radius r in plane, whose parameters are the starting point p_d, the depth l, the edge loop e, and the unit orientation vector $\vec{v}$. Thus, we can specify a particular feature in ϕ_e by giving specific values for p_d, $\vec{v}$, e, and l.

Fig. 4 shows examples of the machining features.

A feature f is *accessible* in a workpiece W if the following conditions are satisfied:



(a) hole-drilling (b) end-milling

Figure 4: Examples of machining features

1. The accessibility volume of f does not intersect with workpiece W, i.e. , $acc(f_i) \cap^* W_{i-1} = \emptyset$.
2. If the class of feature f is hole-drilling, then to ensure proper machining, the entry face of the hole should be a planar surface perpendicular to the hole axis (no similar condition is needed for milling).

3.3. Feature-Based Model

Depending upon available manufacturing facilities, we will have some fixed finite set of feature classes $\Phi = \{\phi_1, \ldots, \phi_n\}$, and for each part that we want to manufacture, we will be interested in describing the part in terms of features from Φ. Suppose we are given a part P and stock S. A *feature-based model* (or FBM) of P and S is any set of features F having the following properties:

1. Each $f \in F$ is an instance of some feature class in Φ.
2. If we subtract the features in F from S, we get P; i.e. , $S - \bigcup_{f \in F} rem(f) = P$.
3. No feature in F is redundant, i.e. , for every feature $f \in F, S - \bigcup_{g \in F - \{f\}} rem(g) \neq P$.

For example, the set of features $\{s1, s2, s3, h1, h2\}$ shown in Fig. 5 is an FBM for the part shown in Fig. 2. Intuitively, an FBM is an interpretation of the delta volume (volume to be machined) as a set of machining features.

Let f and f' be any two distinct features in some FBM. Then f and f' *intersect* each other if $rem(f) \cap^* rem(f') \neq \emptyset$.

3.4. Operation Plan

Each machining feature is associated with a machining operation and vice versa. Given a set of features, we can get the associated machining operations—and we can also determine a partial ordering on these operations, as described in Section 6.

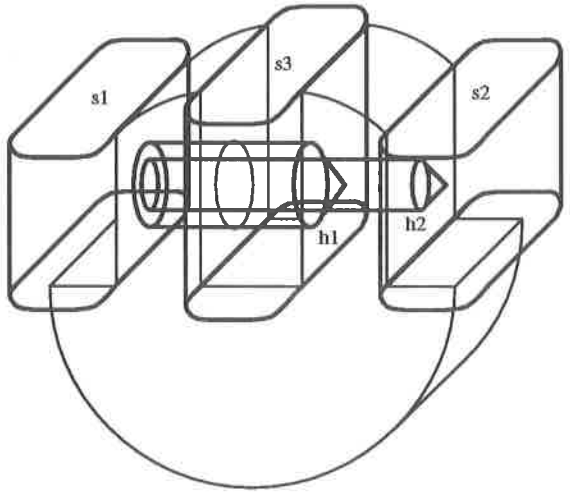


Figure 5: Example of a feature-based model.

Let O be a set of machining operations, and $\prec$ be a partial ordering of O. Then $(O, \prec)$ is an *operation plan* if every total ordering $\{o_1, o_2, \ldots, o_k\}$ of O that is consistent with $\prec$ satisfies the following conditions:

> For each i, let f_i be the feature corresponding to o_i. Let $W_0 = S$, and $W_i = W_{i-1} - rem(f_i)$ for all $i > 0$. Then
>
> **Condition 1:** for all $i > 0$, f_i is accessible in W_{i-1}.
>
> **Condition 2:** each f_i is the smallest feature in its class that can be used to produce W_i from W_{i-1}; i.e., there is no feature $f \in class(f_i)$ such that: $rem(f) \subset rem(f_i)$ and $W_{i-1} - rem(f_i) = W_{i-1} - rem(f)$.

Table 2: Surfaces created by hole-drilling and end-milling features.

Type of feature	Portion of feature boundary	Surface type
hole-drilling	bottom	conical (concave)
	side	cylindrical (concave)
end-milling	bottom	planar
	side	cylindrical or planar

4. IDENTIFYING MACHINING FEATURES

Given solids representing the part P and the stock S, and a set of feature classes Φ, we are interested in finding out which features from Φ can be used to create P. Each machining feature is capable of creating certain types of surfaces. For example, Table 2 presents various types of surfaces which can be created by hole-drilling (shown in Fig. 4(a)) and end-milling (shown in Fig. 4(b)) features.

In our approach, we consider all the part surfaces that need to be created, and try to identify features (i.e., instances of feature classes) which are capable of creating those surfaces. The basic idea behind our approach is given below:

```
1. Let $U_{cr} = b(P) -^* b(S)$ be the set of all faces of $P$ that
   are not faces of $S$.
2. For each face $u \in U_{cr}$, do:
     For each feature class $\phi \in \Phi$, do:
       If the class $\phi$ contains a feature $f$ such that
         (a) $f$ can create $u$ (i.e., $f$ has $u$ as its face),
             and
         (b) $f$ does not intersect the part (i.e., $P \cap^* rem(f) = \emptyset$),
       then identify the maximal feature in $\phi$ that has
         those properties, (i.e., no larger feature from
         $\phi$ has the same properties), and add it to set
         $\mathcal{F}$.
```

The above approach produces features that are maximal (i.e., as large as possible). Later (see Section 6), we trim those features to produce realistic machining features.

As a specific instance of this approach, our research group has developed an algorithm for identifying machining features such as pocket and holes from a given portion of the boundary of the feature. For the details of that algorithm, readers are referred to [4].

As an example, consider the part shown in Fig. 2, and suppose that hole-drilling and end-milling are the only available feature classes. Fig. 6 shows the features identified by our algorithm.

5. GENERATING FEATURE-BASED MODELS

After finding the set $\mathcal{F}$ of all maximal features, we consider various subsets of $\mathcal{F}$ that are sufficient to create the part P from S. In other words, we are interested in subsets $F \subseteq \mathcal{F}$ such that $U_{cr} = \cup^* \{U(f) | f \in F\}$, where $U(f) = \{$all faces of the part P that can be created by $f\}$. Each such set $F \subset \mathcal{F}$ is called a *feature based model* (or FBM). An FBM F is *irredundant* if there is no subset $F' \subset F$ such that F' is also an FBM. Most of the time, we will only be interested in irredundant FBMs.

Since each irredundant FBM is basically a set cover for the set $\mathcal{F}$, we will generate irredundant FBM's using set-covering techniques [19], and use pruning heuristics to discard unpromising FBMs.

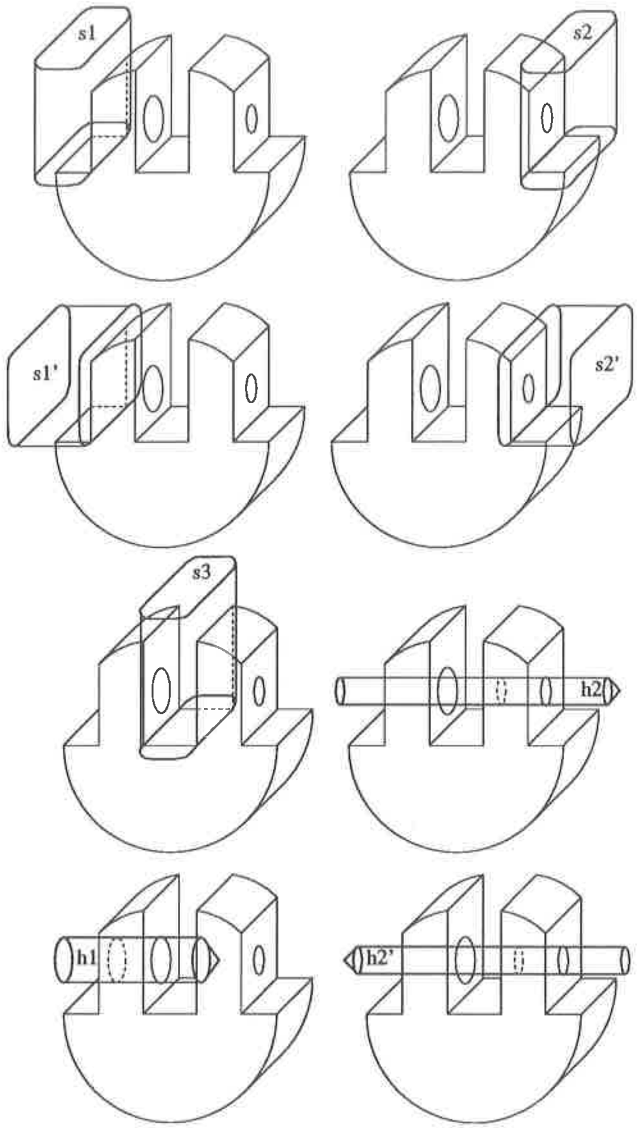
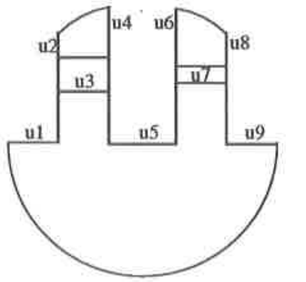


Figure 6: Features identified by our algorithm. Since they are maximal, they exceed the stock volume. Before mapping them to machining operations, we will trim them (see Section 6) to produce realistic machining features.



U(s1) = [u1 u2]
U(s2) = [u8 u9]
U(s1') = [u1 u2]
U(s2') = [u8 u9]
U(s3) = [u4 u5 u6]
U(h1) = [u3]
U(h2) = [u7]
U(h2') = [u7]

Figure 7: The set $U(f)$ for each feature f shown in Fig. 6.

Discarding Unpromising FBMs: Let $L_s(F)$ be the cardinality of the set $\{\vec{v}(f) : f \in F\}$, where $\vec{v}(f)$ is the unit orientation vector for feature f. Then $L_s(F)$ is the number of different directions of approach needed in order to machine F, and (except on 5-axis machines or special purpose fixtures) is a lower bound on the number of setups needed to machine F. Similarly, let $L_{tc}(F)$ be the cardinality of the set $\{(tool(f), \vec{v}(f)) : f \in F\}$, where $tool(f)$ is the tool associated with feature f. Then $L_{tc}(F)$ is a lower bound on the number of tool changes needed in order to machine F.

If two FBMs F and F' have same sets of removal volumes but different sets of accessibility volumes, then the expected machining accuracy of F and F' is same, but the number of setups and/or tool changes might be different. In this case, we consider F' unpromising if either of the following conditions is satisfied:

- $L_s(F) \leq L_s(F')$ and $L_{tc}(F) < L_{tc}(F')$ (i.e., F is believed to require no more setups than F', and fewer tool changes);
- $L_{tc}(F) \leq L_{tc}(F')$ and $L_s(F) < L_s(F')$ (i.e., F is believed to require no more tool changes than F', and fewer setups).

We can also use heuristics to identify sets of symmetric features, and modify the set-covering approach to generate only those FBMs which contain complete set of symmetric features. As an example, Fig. 7 presents the set $U(f)$ for each feature f shown in Fig. 6. In this case, $s1$ is symmetric to $s2$, and $s1'$ is symmetric to $s2'$. Thus as shown in Fig. 8, we would generate FBMs that contain $s1$ and $s2$, and FBMs that contain $s1'$ and $s2'$, but not FBMs that contain $s1$ and $s2'$, nor FBMs that contain $s1'$ and $s2$.

6. GENERATING OPERATION PLANS

After generating FBMs, the next step is to generate the associated machining operations along with their partial orderings. Since an FBM consists of maximal features, these features are often larger than necessary. Therefore, before generating operation plans, we trim the features in an FBM, to produce realistic machining features.

If F is an FBM and R is a solid, then trimming the features in F with respect to R involves the following two steps (Fig. 9 illustrates this on FBM 1 of Fig. 8, in the case where R is the stock S):

1. First, shorten f by eliminating (as much as possible) those portions of $rem(f)$ that are outside R and finding a new datum point p_d (as illustrated in Fig. 9(b)).

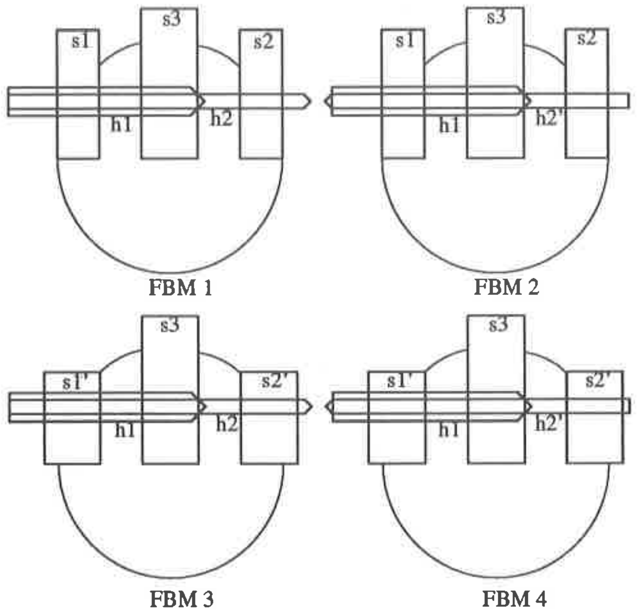
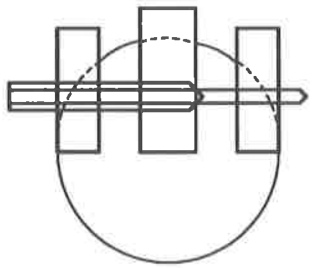
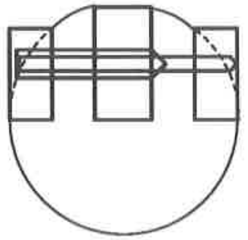


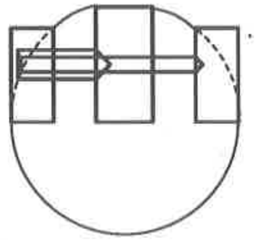
Figure 8: FBMs generated by our algorithm.



(a): before trimming



(b): after the first trimming step



(c): after the second trimming step

Figure 9: Trimming FBM 1 (of Fig. 8) with respect to the stock.

Table 2: Surfaces created by hole-drilling and end-milling features.

Type of feature	Portion of feature boundary	Surface type
hole-drilling	bottom	conical (concave)
	side	cylindrical (concave)
end-milling	bottom	planar
	side	cylindrical or planar

4. IDENTIFYING MACHINING FEATURES

Given solids representing the part P and the stock S, and a set of feature classes Φ, we are interested in finding out which features from Φ can be used to create P. Each machining feature is capable of creating certain types of surfaces. For example, Table 2 presents various types of surfaces which can be created by hole-drilling (shown in Fig. 4(a)) and end-milling (shown in Fig. 4(b)) features.

In our approach, we consider all the part surfaces that need to be created, and try to identify features (i.e., instances of feature classes) which are capable of creating those surfaces. The basic idea behind our approach is given below:

1. Let $U_{cr} = b(P) -^{*} b(S)$ be the set of all faces of P that are not faces of S.
2. For each face $u \in U_{cr}$, do:

   For each feature class $\phi \in \Phi$, do:

   If the class ϕ contains a feature f such that
   - (a) f can create u (i.e., f has u as its face), and
   - (b) f does not intersect the part (i.e., $P \cap^{*} rem(f) = \emptyset$),

   then identify the *maximal* feature in ϕ that has those properties, (i.e., no larger feature from ϕ has the same properties), and add it to set $\mathcal{F}$.

The above approach produces features that are maximal (i.e., as large as possible). Later (see Section 6), we trim those features to produce realistic machining features.

As a specific instance of this approach, our research group has developed an algorithm for identifying machining features such as pocket and holes from a given portion of the boundary of the feature. For the details of that algorithm, readers are referred to [4].

As an example, consider the part shown in Fig. 2, and suppose that hole-drilling and end-milling are the only available feature classes. Fig. 6 shows the features identified by our algorithm.

5. GENERATING FEATURE-BASED MODELS

After finding the set $\mathcal{F}$ of all maximal features, we consider various subsets of $\mathcal{F}$ that are sufficient to create the part P from S. In other words, we are interested in subsets $F \subseteq \mathcal{F}$ such that $U_{cr} = \cup^{*}\{U(f) | f \in F\}$, where $U(f) =$ {all faces of the part P that can be created by f}. Each such set $F \subset \mathcal{F}$ is called a *feature based model* (or FBM). An FBM F is *irredundant* if there is no subset $F' \subset F$ such that F' is also an FBM. Most of the time, we will only be interested in irredundant FBMs.

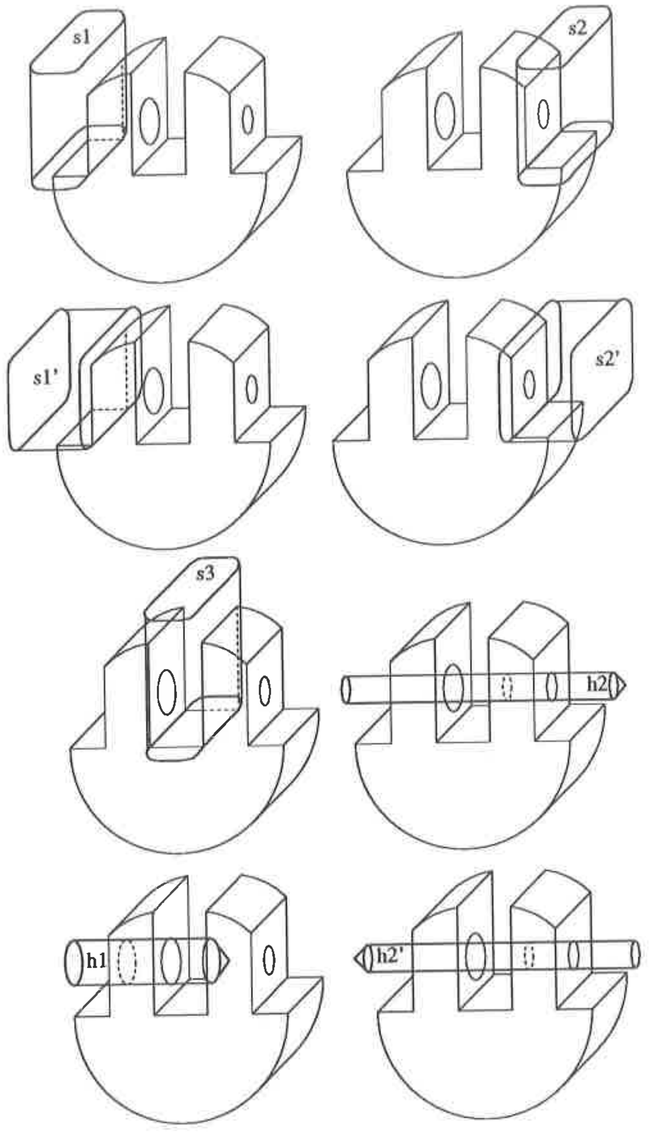
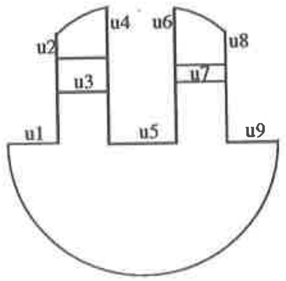


Figure 6: Features identified by our algorithm. Since they are maximal, they exceed the stock volume. Before mapping them to machining operations, we will trim them (see Section 6) to produce realistic machining features.



U(s1) = [u1 u2]
U(s2) = [u8 u9]
U(s1') = [u1 u2]
U(s2') = [u8 u9]
U(s3) = [u4 u5 u6]
U(h1) = [u3]
U(h2) = [u7]
U(h2') = [u7]

Figure 7: The set $U(f)$ for each feature f shown in Fig. 6.

Since each irredundant FBM is basically a set cover for the set $\mathcal{F}$, we will generate irredundant FBM's using set-covering techniques [19], and use pruning heuristics to discard unpromising FBMs.

Discarding Unpromising FBMs: Let $L_s(F)$ be the cardinality of the set $\{\vec{v}(f) : f \in F\}$, where $\vec{v}(f)$ is the unit orientation vector for feature f. Then $L_s(F)$ is the number of different directions of approach needed in order to machine F, and (except on 5-axis machines or special purpose fixtures) is a lower bound on the number of setups needed to machine F. Similarly, let $L_{tc}(F)$ be the cardinality of the set $\{(tool(f), \vec{v}(f)) : f \in F\}$, where $tool(f)$ is the tool associated with feature f. Then $L_{tc}(F)$ is a lower bound on the number of tool changes needed in order to machine F.

If two FBMs F and F' have same sets of removal volumes but different sets of accessibility volumes, then the expected machining accuracy of F and F' is same, but the number of setups and/or tool changes might be different. In this case, we consider F' unpromising if either of the following conditions is satisfied:

- $L_s(F) \leq L_s(F')$ and $L_{tc}(F) < L_{tc}(F')$ (i.e., F is believed to require no more setups than F', and fewer tool changes);
- $L_{tc}(F) \leq L_{tc}(F')$ and $L_s(F) < L_s(F')$ (i.e., F is believed to require no more tool changes than F', and fewer setups).

We can also use heuristics to identify sets of symmetric features, and modify the set-covering approach to generate only those FBMs which contain complete set of symmetric features. As an example, Fig. 7 presents the set $U(f)$ for each feature f shown in Fig. 6. In this case, $s1$ is symmetric to $s2$, and $s1'$ is symmetric to $s2'$. Thus as shown in Fig. 8, we would generate FBMs that contain $s1$ and $s2$, and FBMs that contain $s1'$ and $s2'$, but not FBMs that contain $s1$ and $s2'$, nor FBMs that contain $s1'$ and $s2$.

6. GENERATING OPERATION PLANS

After generating FBMs, the next step is to generate the associated machining operations along with their partial orderings. Since an FBM consists of maximal features, these features are often larger than necessary. Therefore, before generating operation plans, we trim the features in an FBM, to produce realistic machining features.

If F is an FBM and R is a solid, then trimming the features in F with respect to R involves the following two steps (Fig. 9 illustrates this on FBM 1 of Fig. 8, in the case where R is the stock S):

1. First, shorten f by eliminating (as much as possible) those portions of $rem(f)$ that are outside R and finding a new datum point p_d (as illustrated in Fig. 9(b)).

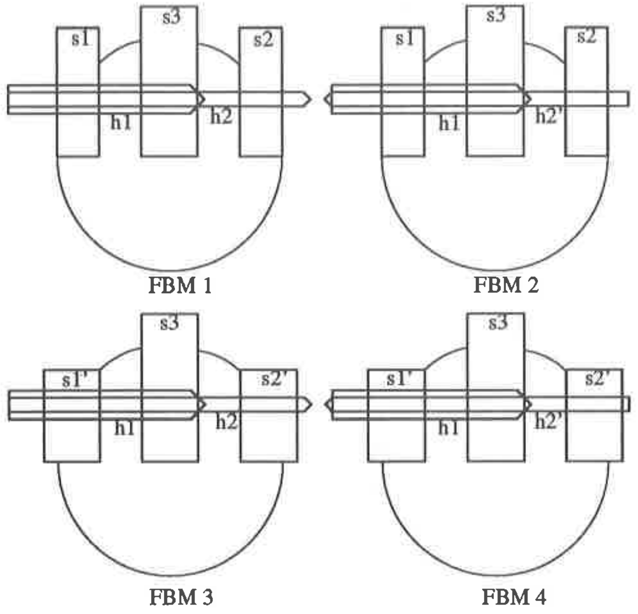
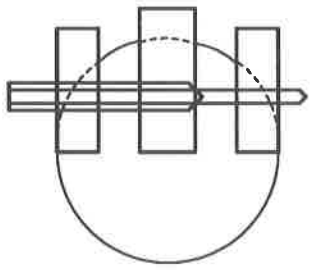
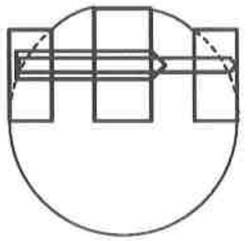


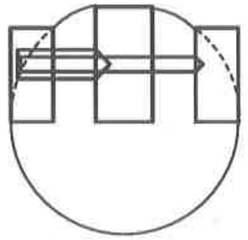
Figure 8: FBMs generated by our algorithm.



(a): before trimming



(b): after the first trimming step



(c): after the second trimming step

Figure 9: Trimming FBM 1 (of Fig. 8) with respect to the stock.

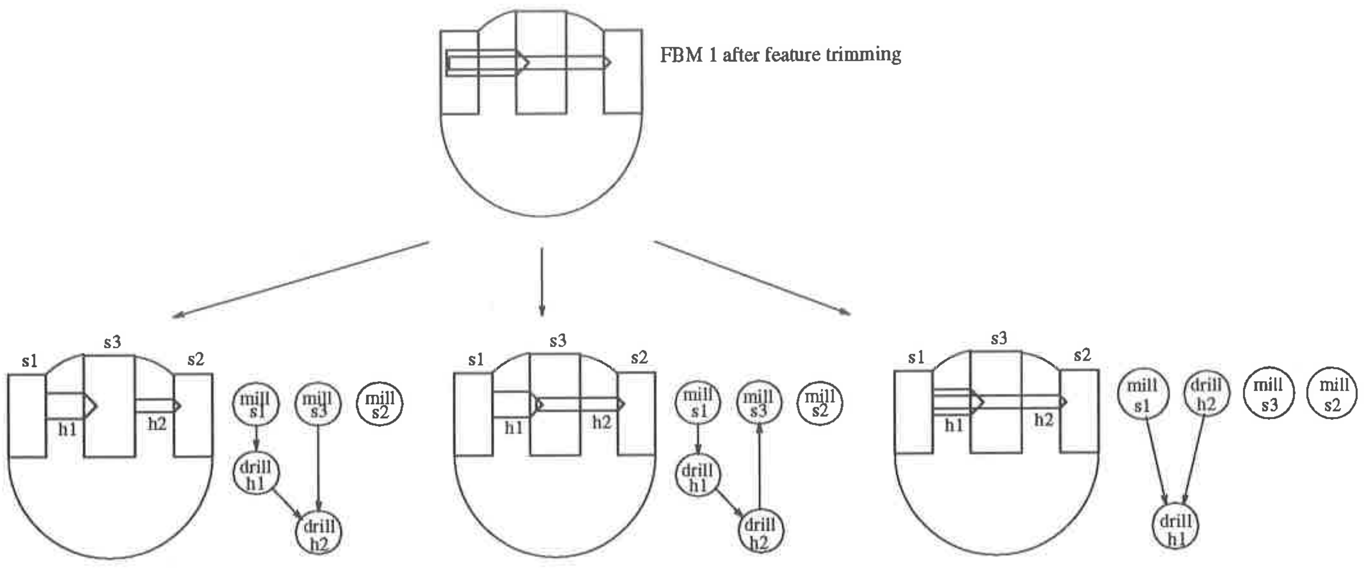


Figure 10: Generating Operation Plans from FBM 1

2. The removal volume $rem(f)$ is a swept volume produced by sweeping the cutting-tool volume T_v along a trajectory t that starts at the datum point p_d. If the trajectory t can be shortened without changing the datum point p_d or the total volume removed from R by the FBM, then trim f by shortening t (as illustrated in Fig. 9(c)).

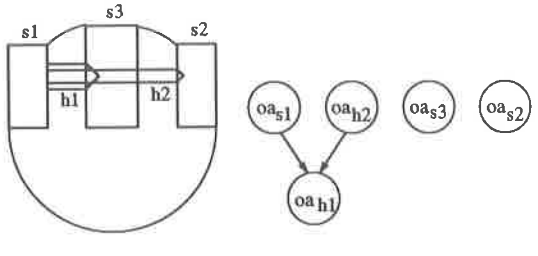
We generate operation plans as follows:

1. Trim each feature of F with respect to the stock S.
2. $\mathcal{O} = \emptyset$. ($\mathcal{O}$ will eventually be the set of operation plans returned in Step 5.)
3. For every partial ordering $\prec$ on F that totally orders intersecting features of F, do:
    (a) Let $f_1, \ldots, f_n$ be any total ordering of F that is consistent with $\prec$. (Such a total ordering can easily be generated using topological sorting [19]. This total ordering is not unique, but since $\prec$ totally orders intersecting features, we can prove that we will get exactly the same operation plan regardless of which total ordering is produced by the topological sorting algorithm.)
    (b) Trim each f_i with respect to $W_i = S -^* (f_1 \cup^* \ldots \cup^* f_{i-1})$. If f_i is not accessible in W_i after trimming, then discard $\prec$ and skip Step (c).
    (c) Otherwise, map each f_i to its associated machining operation o_i, and define $o_i \prec o_j$ if and only if $f_i \prec f_j$. Then the operation set $O = \{o_1, \ldots, o_n\}$ along with the partial ordering $\prec$ is an operation plan. If this operation plan is unpromising (see below) then discard it. Otherwise, insert the operation plan $(O, \prec)$ into $\mathcal{O}$ (i.e., $\mathcal{O} := \mathcal{O} \cup \{(O, \prec)\}$).
4. Until $\mathcal{O}$ contains no mergeable operation plans (see below), do the following:
   for every pair of mergeable operation plans in $\mathcal{O}$, remove them from $\mathcal{O}$ and replace them with the merged operation plan.
5. Return $\mathcal{O}$.

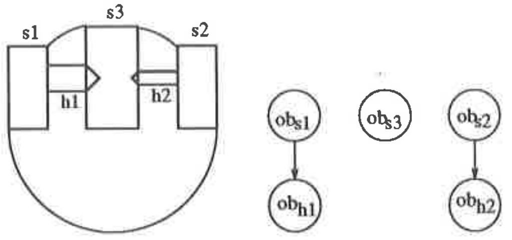
In the above algorithm, suppose the operation plans $(O_1, \prec_1)$ and $(O_2, \prec_2)$ consist of identical operations (i.e., $O_1 = O_2$) and nearly identical partial orderings (i.e., $\prec_1 = \prec_2$ except that there are operations o, o' such that $o \prec_1 o'$ and $o' \prec_2 o$. Then these two operation plans are *mergeable*, resulting in the *merged plan* $(O_1, \prec_3)$, where $\prec_3$ is identical to $\prec_1$ and $\prec_2$ except that it does not order o and o'.

As an example, consider FBM 1 of Fig. 8. Because of the cylindrical stock boundary, if the hole $h1$ is machined before the slot $s1$, then h_1's entry face will be a curved surface and will pose an accessibility problem. Therefore, the above procedure will generate no operation plan in which $h1 \prec s1$. Fig. 10 shows three different operation plans produced from FBM 1.

Identifying Unpromising Operation Plans: We will consider O to be unpromising if it contains machining operations whose dimensions and tolerances appear unreasonable. Examples include the following: a hole-drilling operation whose L/D ratio is too large; a recess-boring operation whose r/D ratio is too large; two concentric hole-drilling operations with tight concentricity tolerance and opposite approach directions. For example, if we restrict $L/D < 6$, then Design 2 can only be machined by drilling the two holes from opposite approach directions—and thus no operation plan resulting from FBM 1 or FBM 3 is feasible.



(a): O_a



(b): O_b

Figure 11: Two Different Operation Plans

7. MANUFACTURABILITY EVALUATION

7.1. Estimating Achievable Machining Accuracy

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give *design tolerance* specifications on the nominal geometry, to specify how large these variations are allowed to be. To verify whether or not a given operation plan will produce the desired design tolerances, we want to estimate what tolerances the operations can achieve. We have developed mathematical and empirical techniques for doing this; for details see [1].

Examples: For the part shown in Fig. 2, Fig. 11 shows two operation plans O_a and O_b. O_a was generated from FBM 1 (it is the rightmost of the plans shown in Fig. 10, and O_b was generated from FBM 2. The details of these two plans are presented in the Appendix. As we discuss later in Section 7.2, O_a is the shortest-production-time plan for Design 1, and O_b is the shortest-production-time plan for Design 2, where Design 1 and Design 2 are as described in Section 3.1.

Tables 3 and 4 present the estimated achievable tolerances for operation plan O_a and O_b respectively. Note that because of the setup change between the two drilling operations in operation plan O_b, the achievable concentricity tolerance between the two holes is worse than in O_a. If designer had specified a tighter concentricity tolerance, then in O_b we would have not been able to achieve that tolerance with drilling operations.

Table 3: Achievable tolerances for operation plan O_a

surface(s)	tolerance type	operation(s)	upper limit	lower limit
$u3$	diameter	oa_{h1}	0.25	0.00
$u7$	diameter	oa_{h2}	0.20	0.00
$u4$-$u6$	length	oa_{s3}	0.10	-0.10
$u3$-$u7$	concentricity	oa_{h1},oa_{h2}	0.10	N/A

Table 4: Achievable tolerances for operation plan O_b

surface(s)	tolerance type	operation(s)	upper limit	lower limit
$u3$	diameter	ob_{h1}	0.20	0.00
$u7$	diameter	ob_{h2}	0.15	0.00
$u4$-$u6$	length	ob_{s3}	0.10	-0.10
$u3$-$u7$	concentricity	ob_{h1},ob_{h2}	0.40	N/A

7.2. Estimating Production Cost and Time

Significant amount of research has been done in production cost and time estimation for machining operations. Formulas for estimating cost and time can be found in handbooks such as [14, 15]. Most of the formulas used in following examples are given in [13].

Examples. Tables 5 and 6 present time estimates for operation plans O_a and O_b. In estimating production time, we have added half the tool diameter to each hole length to account for lead-in and break-through. Similarly, for milling operations, we have added the tool diameter to each slot length to account for lead-in and break-through. We assume that the part will held in a vise. The setup-change time for the vise is taken from [15]. Although we can similarly estimate the production costs for O_a and O_b, we omit this for the sake of brevity.

7.3. Manufacturability Rating

Depending upon particular manufacturing objective (such as fastest production time, lowest cost, highest production quality, and so forth), a suitable manufacturability rating can be formulated. As an example, suppose we use the following manufacturability rating, which is inversely proportional to production time:

$$M_R = \mathrm{MMR}_{\mathrm{eff}} / \mathrm{MMR}_{\mathrm{max}},$$

where $\mathrm{MMR}_{\mathrm{max}}$ is the maximum achievable metal removal rate in the given feature classes Φ, and

$$\mathrm{MMR}_{\mathrm{eff}} = \frac{\text{volume to be machined}}{\text{estimated production time}}.$$

If the design requires a high number of setup changes, tool changes, and slower manufacturing operations, then the value of M_R will be low. If the design cannot be machined using features from Φ, then $M_R = 0$.

Over all of the operation plans for Design 1, O_a is the one that has the smallest production time, and thus the highest value for M_R. In particular, if we use $\mathrm{MMR}_{\mathrm{max}} =$

Table 5: Time estimates for various operations of operation plan O_a

Operation	oa_{s1}	oa_{s2}	oa_{s3}	oa_{h2}	oa_{h1}	2 setup changes	3 tool changes	Total time
Time (min)	2.5	2.5	4.0	1.33	0.60	3.0	0.5	14.43

Table 6: Time estimates for various operations of operation plan O_b

Operation	ob_{s1}	ob_{s2}	ob_{s3}	ob_{h2}	ob_{h1}	3 setup changes	3 tool changes	Total time
Time (min)	2.5	2.5	4.0	0.34	0.38	4.5	0.5	14.72

$30cm^3/min$, then $M_R = 0.33$. Similarly, out of all of the operation plans for Design 2, O_b is the one with the smallest production time, and thus the highest value for M_R. In particular, if $\text{MMR}_{\max} = 30cm^3/min$, then $M_R = 0.29$.

Note that Design 1 requires more volume to be machined, but because of reduced setup time it can be machined faster then Design 2. Also note that resulting concentricity tolerance for Design 2 is poor compared to Design 1. If a tighter concentricity tolerance were required, then the manufacturability rating for Design 2 would be worse due to necessity of finishing operations which would increase the production time.

The manufacturability rating described above can be easily modified to account for production cost and quality aspects by adding corresponding terms.

8. CONCLUSIONS

In this paper, we have described a systematic way to generate and evaluate the alternative operation plans for a given design. This work represents a step toward our long-term goal of developing ways for automated manufacturability evaluation of designs. Some of the benefits of our approach are listed below:

1. By using features that correspond directly to machining operations, we have incorporated the process-related information in the features themselves. This allows us to estimate the production cost and quality without going through a very elaborate process-planning step.
2. As opposed to existing rule-based approaches, our approach is based on theoretical foundations, which we hope will enable us to make rigorous statements about the soundness, completeness, efficiency, and robustness of the approach.
3. Since we consider various alternative ways of machining the part, the conclusions about the manufacturability of the proposed design will be more realistic than if we considered just one alternative.

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

ACKNOWLEDGEMENTS

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APPENDIX

Table 8 gives details of operation plan O_a for machining Design 1, and Table 9 gives details of operation plan O_b for machining Design 2. Various tools used in these plans are described in Table 7.

Table 7: Description of tools.

tool number	tool type	parameters
EM1	HSS end mill	tool dia = 40 mm number of teeth = 4
TD2	HSS STD drill	tool dia = 20 mm
TD3	HSS STD drill	tool dia = 30 mm
TD4	HSS STD drill	tool dia = 10 mm
TD5	HSS STD drill	tool dia = 15 mm

Table 8: Details of operation plan O_a for Design 1.

name	type	tool	parameters	feed & speed
oa_{s1}	slot milling	EM1	slot width = 15mm slot length = 50mm; 5 passes	feed = 0.15 mm/tooth; RPM = 300

oa_{s2}	slot milling	EM1	slot width = 15mm;
			slot length = 50mm;
			5 passes
				feed = 0.15 mm/tooth;
				RPM = 300

oa_{s3}	slot milling	EM1	slot width = 40mm;
			slot length = 50mm;
			8 passes
				feed = 0.15 mm/tooth;
				RPM = 300

oa_{h2}	hole drilling	TD1	hole diam = 20mm; hole length = 70mm;	feed = 0.20 mm/rev; RPM = 300
oa_{h1}	hole drilling	TD2	hole diam = 30mm; hole length = 15mm	feed = 0.25 mm/rev; RPM = 200

Table 9: Details of Operation plan O_b for Design 2.

name	type	tool	parameters	feed & speed

ob_{s1}	slot milling	EM1	slot width = 15mm;
			slot length = 50mm;
			5 passes
				feed = 0.15 mm/tooth;
				RPM = 300

ob_{s2}	slot milling	EM1	slot width = 15mm;
			slot length = 50mm;
			5 passes
				feed = 0.15 mm/tooth;
				RPM = 300

ob_{s3}	slot milling	EM1	slot width = 40mm;
			slot length = 50mm;
			8 passes
				feed = 0.15 mm/tooth;
				RPM = 300

ob_{h2}	hole drilling	TD3	hole diam = 10mm; hole length = 15mm;	feed = 0.10 mm/rev; RPM = 600
ob_{h1}	hole drilling	TD4	hole diam = 15mm; hole length = 15mm;	feed = 0.15 mm/rev; RPM = 400