CHAPTER 21

Planning for Manufacturability Analysis

21.1 Introduction

Process planning is the task of preparing detailed operating instructions for transforming an engineering design into a final product. Most work on Computer-Aided Process Planning (CAPP) has focused on the development of process plans for mechanical parts.

Variant process planning, which is the basis for most commercial CAPP systems, is basically a case-based reasoning technique (see Section 24.1) in which the case adaptation is done manually by a human user. In generative process planning, the process plan is developed automatically by the computer. The development of generative systems has been a subject of much research, and there is a huge number of publications on that topic (for a comprehensive review, see [471]). However, due to the difficulty of the problem, few successful commercial systems exist.

Manufacturability analysis—the task of giving estimates of how easy it will be to manufacture a proposed design—is somewhat easier than process planning because it does not require generating all the details of the process plan. Manufacturability analysis is useful in order to help designers produce designs that are easier to manufacture.

IMACS (Interactive Manufacturability Analysis and Critiquing System) is a computer system for analyzing the manufacturability of designs for machined parts. As shown in Figure 21.1, IMACS evaluates the manufacturability of a proposed design by generating and evaluating manufacturing operation plans. Our description of IMACS is based largely on the one in Nau *et al.* [417].

21.2 Machined Parts

A machined *part*, P, is the final component created by executing a set of machining operations on a piece of *stock*, S. For example, Figure 21.2 shows a socket P_0 and the

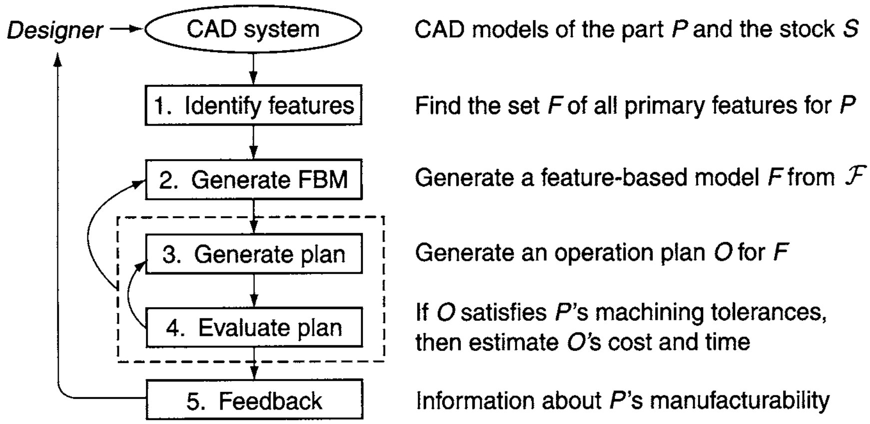


Figure 21.1 Basic approach used in IMACS.

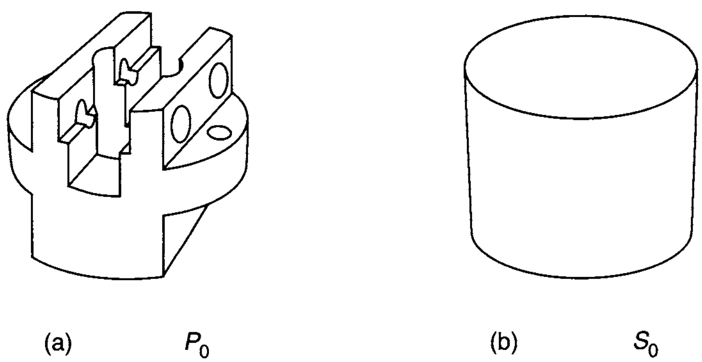


Figure 21.2 The socket P_0 (a) and the stock S_0 (b).

stock S_0 from which P_0 is to be produced. Note that the goal to be achieved (i.e., the part to be produced) is represented not as a set of atoms or state variables but instead as a CAD model (which IMACS represents using a commercial solid-modeling system).

An *operation plan* is a sequence of machining operations capable of creating the part P from the stock S. Because it would be physically impossible to produce P's *exact* geometry, designers give *design tolerance* specifications (see Figure 21.3) to specify how much variation from the nominal geometry is allowable in any physical realization of P. A plan is considered capable of achieving the goal if it can create an instance of P that satisfies the design tolerances.

A *workpiece* is the intermediate object produced by starting with S and performing zero or more machining operations. Currently, the machining operations

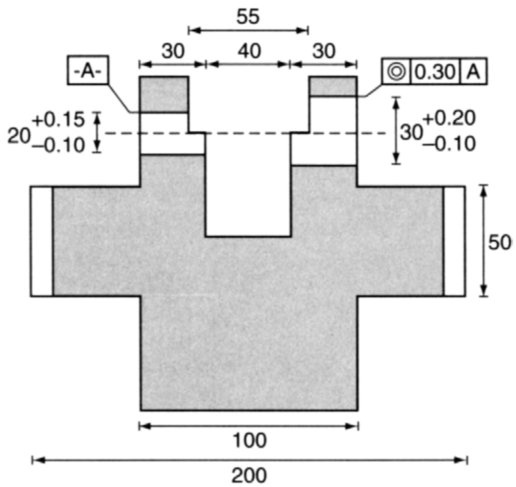


Figure 21.3 Dimensions and tolerances for the socket P_0.

considered in IMACS include end milling, side milling, face milling, and drilling operations on a three-axis vertical machining center. Each machining operation creates a *machining feature.* Different researchers use different definitions of machining features; as shown in Figure 21.4, IMACS considers a machining feature to include information about the type of machining operation, the material removal volume (the volume of space in which material can be removed), and the accessibility volume (the volume of space needed for access to the part).

21.3 Feature Extraction

IMACS incorporates algorithms to recognize portions of a CAD model that correspond to machining features [455]. One difficulty here is that depending on the geometry of P, there can be many—sometimes infinitely many—different machining features capable of creating various portions of P. In IMACS, this is addressed by defining a *primary* feature to be a feature that contains as much of the stock as possible without intersecting with P and as little space as possible outside the stock. Figure 21.5 shows examples of primary and nonprimary features; for more details, see Regli *et al.* [455].

In every operation plan that IMACS will ever want to consider, each machining operation will create either a primary feature or a truncation of a primary feature—and the number of primary features for a part is always finite (in fact, polynomial). Thus, IMACS's first step is to find the set $\mathcal{F}$ of all primary features for P and S. For example, for the socket P_0, the set $\mathcal{F}$ contains 22 primary features, a few of which are shown in Figure 21.6.

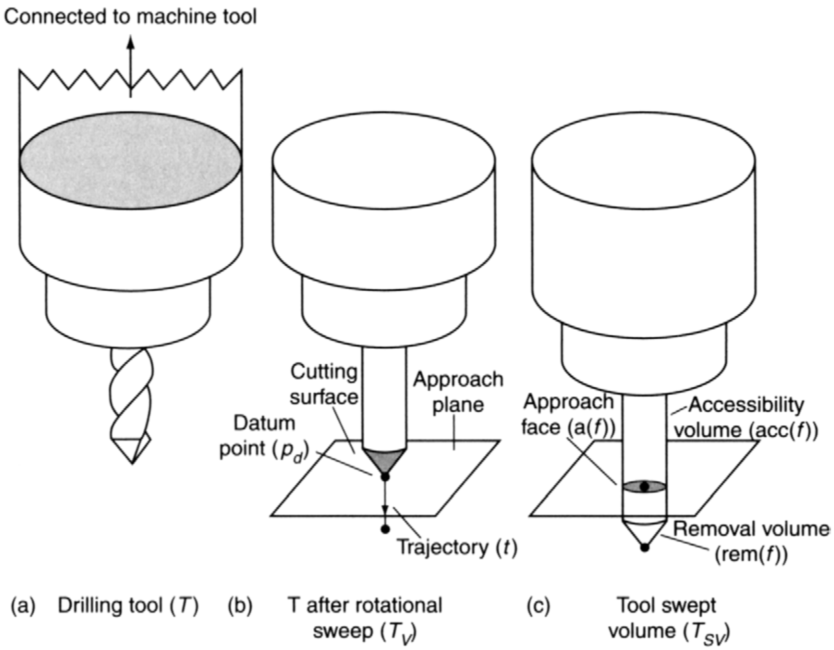


Figure 21.4 Example of a machining operation.

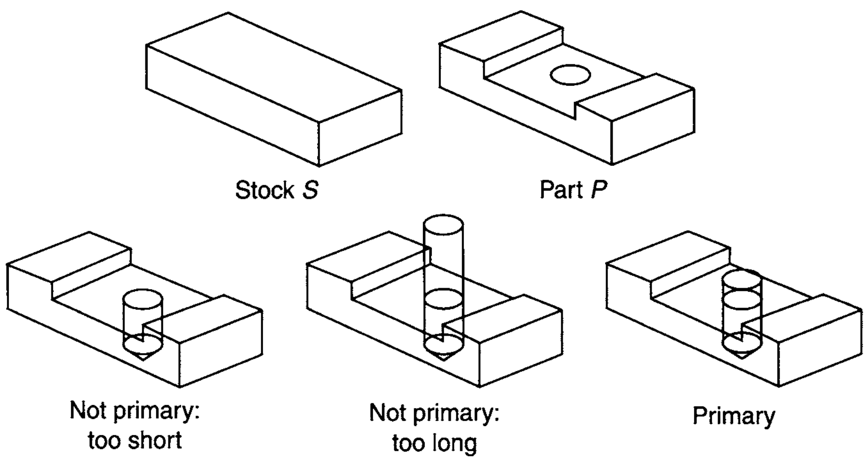


Figure 21.5 Nonprimary and primary drilling features.

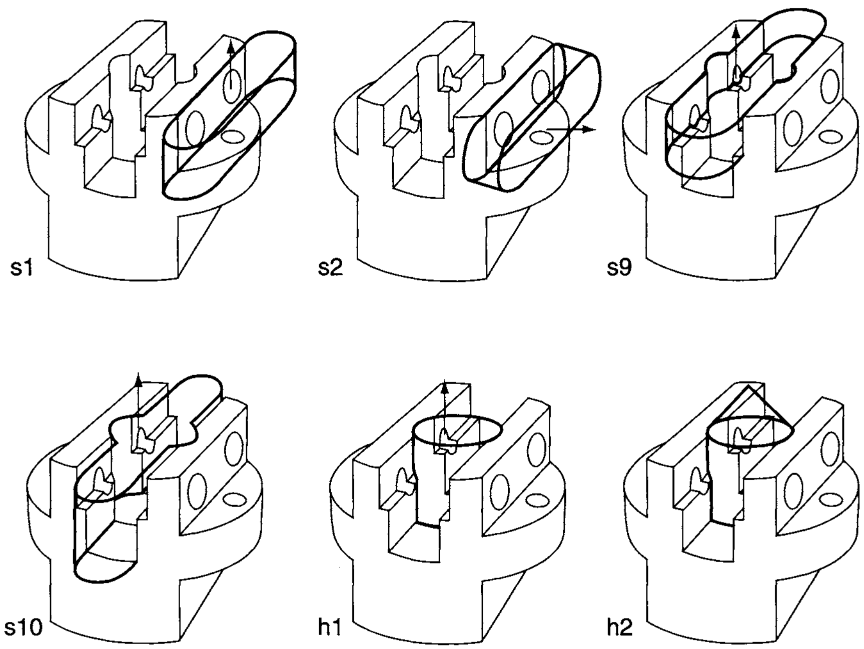


Figure 21.6 A few of the 22 primary features for the socket P_0. $s1, s2, s9,$ *and* $s10$ are end-milling features; $h1$ and $h2$ are drilling features.

Machining operations correspond to elementary actions, and machining features correspond to tasks. $\mathcal{F}$ corresponds to the set of all tasks that might ever be relevant for achieving the goal.

21.4 Generating Abstract Plans

Figure 21.6 shows that the features in $\mathcal{F}$ may overlap in complicated ways, and some of them are redundant (e.g., it is not necessary to machine both s1 and s2). A *feature-based model* (FBM) is any nonredundant subset of features $F \subseteq \mathcal{F}$ such that subtracting those features from S produces P and none of the features are redundant. For example, Figure 21.7 shows an FBM, FBM1, for the socket P_0.

Each FBM corresponds to a set of tasks: if we can machine the features in the FBM, this will create the part. In general, the number of FBMs is exponential in the number of primary features. As an example, for the socket P_0, $\mathcal{F}$ contains 22 primary features from which one can form 512 FBMs. From a manufacturing point of view, some FBMs are better than others. We would like to find an optimal one—but obviously we do not want to examine every possible FBM in order to accomplish this.

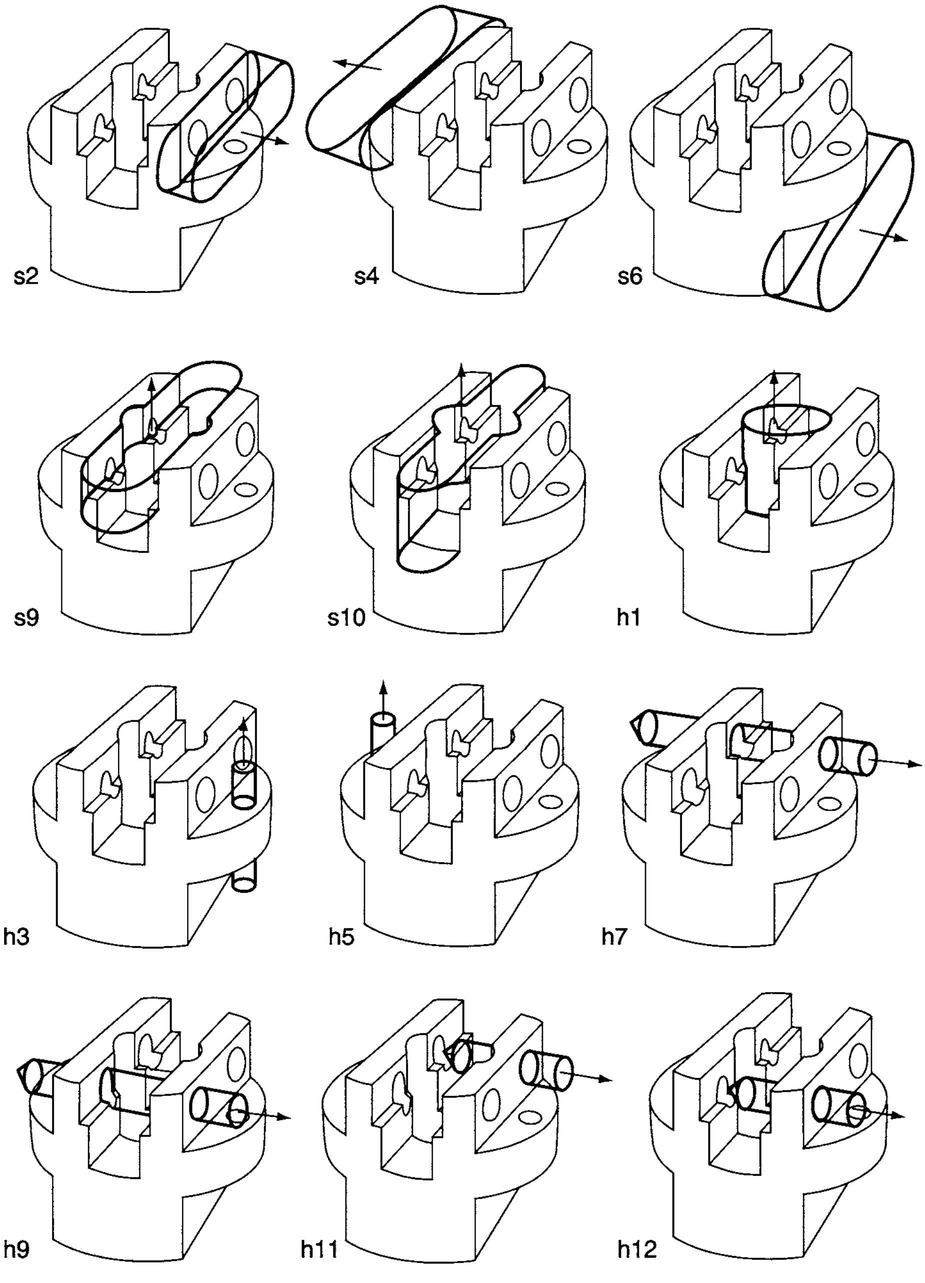


Figure 21.7 Feature-based model FBM1 for the socket P_0.

To avoid looking at every FBM, IMACS does a depth-first branch-and-bound search to generate and test FBMs one at a time, pruning unpromising FBMs as described in Section 21.8. To measure how good a plan is, IMACS uses an estimate of the plan's manufacturing time, as described in Section 21.7. A better measure would also incorporate estimates of production cost: this was not done in IMACS because IMACS is a prototype, but it would be straightforward to accomplish.

As an example of how much the branch-and-bound search reduces the size of the search space, IMACS generates only 16 of the 512 FBMs for the socket P_0.

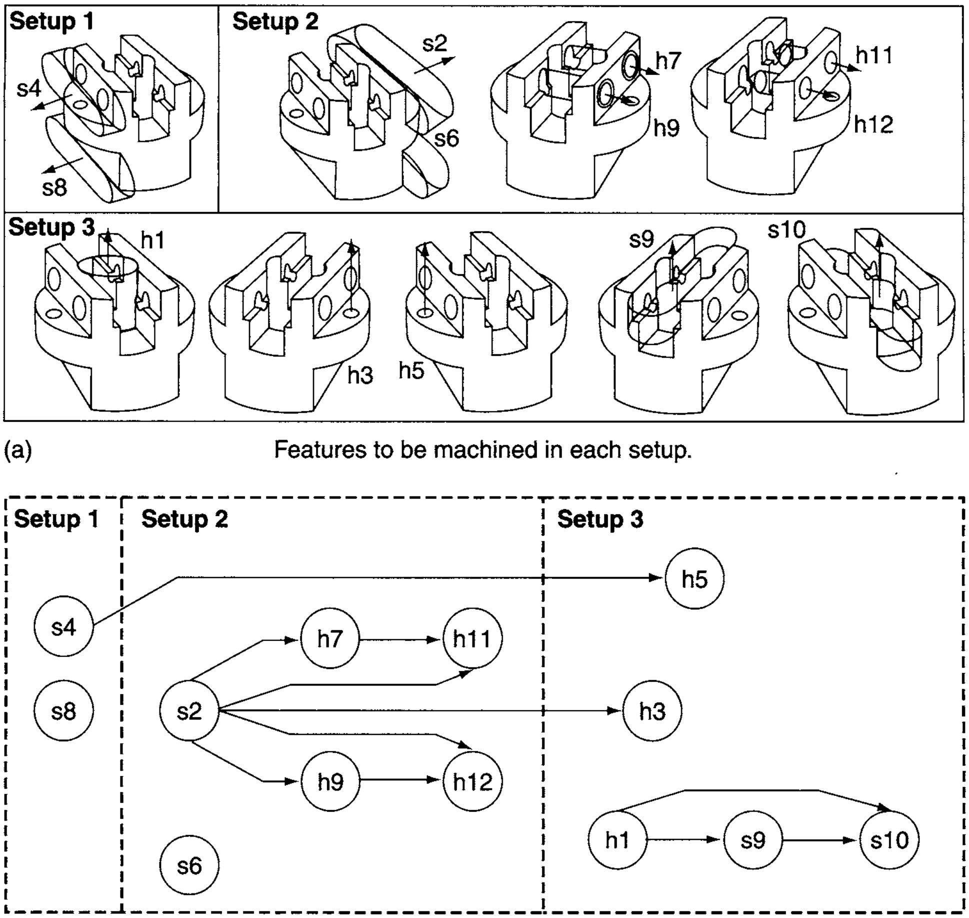
21.5 Resolving Goal Interactions

An FBM corresponds to a set of tasks in which no ordering constraints have yet been imposed. To resolve goal interactions, IMACS adds ordering constraints as follows.

1. *Identify ordering constraints.* Due to complex geometric interactions (accessibility, etc.), some features must precede others. For example, in Figure 21.8, the hole h1 must be machined before the slot s9 in order to achieve reasonable machining tolerances and avoid tool breakage.
2. *Linearize.* Next IMACS generates all total orderings consistent with the precedences. If no such total ordering can be found, IMACS considers the FBM F to be unmachinable and discards it. Unlike the typical approaches used in AI planners, there would be no point in adding additional operators: they would just create redundant features, and if there is a feasible way to machine the part, it will be found among the other FBMs.
3. *Modify goals.* Suppose features f and g overlap, and f precedes g in some total ordering. Then when we machine f, we are also machining part of g. We don't want to machine that same portion of g again later in the sequence because we would merely be machining air. Thus, IMACS truncates g to remove the portion covered by f. As an example, several of the features shown in Figure 21.8 (a) were produced by truncating the corresponding features in FBM1.
4. *Unlinearize.* Once the truncated features have been produced, several of the resulting FBMs may have identical features but different precedence constraints. In such cases the precedence constraints that differ can be removed, translating the total orders into partial orders. For example, Figure 21.8 (b) shows the partial order for the FBM of Figure 21.8 (a).

21.6 Additional Steps

To obtain an operation plan from the partially ordered FBM, IMACS uses the following steps.



(a) Features to be machined in each setup.

(b) Ordering constraints.

Figure 21.8 An operation plan derived form FBM1. This plan is the optimal one for making P_0. Note that each feature is either a primary feature from FBM1 or a truncation of a primary feature from FBM1. The details of the machining processes are shown in Table 21.1.

1. *Incorporate finishing operations.* For faces with tight surface finishes or tolerances, IMACS adds finishing operations, with precedence constraints to make them come after the corresponding roughing operations. Currently, one finishing operation per face is allowed.
2. *Determine setups.* On a three-axis vertical machining center, features cannot be machined in the same setup unless they have the same approach direction. This and the partial ordering constraints can be used to determine which features can be machined in the same setup, as shown in Figure 21.8 (b). This technique is a version case of plan merging (see Section 24.4).

Table 21.1 Cutting parameters for the operation plan.

Feature name	*Feature type*	*Tool diameter (mm)*	*Feed rate (mm/min)*	*Number of passes*	*Pass length (mm)*
s4	End-milling	50	166	2	225
s8	End-milling	50	166	2	225
s2	End-milling	50	166	2	225
s6	End-milling	50	166	2	225
h7	Drilling	20	244	1	106
h9	Drilling	20	244	1	106
h11	Drilling	30	203	1	39
h12	Drilling	30	203	1	39
h1	Drilling	75	108	1	172.5
h3	Drilling	20	244	1	56
h5	Drilling	20	244	1	56
s9	End-milling	50	166	1	250
s10	End-milling	40	207	3	240

3. *Determine process details.* To select cutting parameters such as those shown in Table 21.1, IMACS uses the recommendations in a standard handbook [113]. The maximum recommended cutting parameters are used, rather than attempting to select optimal cutting parameters; thus IMACS's estimates involve considerable approximation.

As shown in Figure 21.9, these steps correspond to a task decomposition like the ones in HTN planning (see Chapter 11).

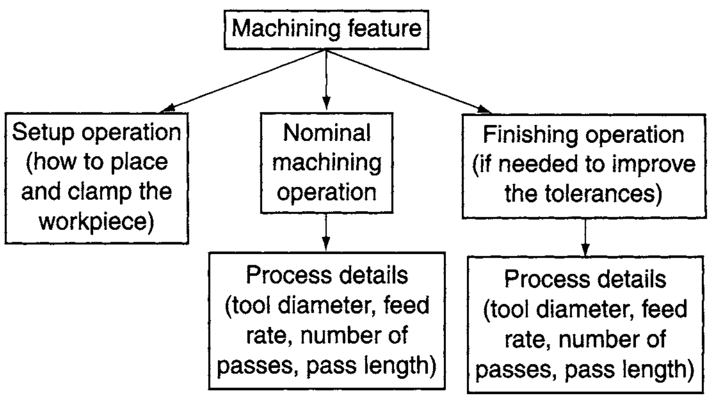


Figure 21.9 Task decomposition in IMACS.

Because each FBM can lead to several different operation plans, IMACS does the above steps inside a depth-first branch-and-bound search, evaluating the plans as described in Section 21.7 in order to find the optimal operation plan. For example, Figure 21.8 and Table 21.1 show the operation plan IMACS finds for the socket P_0.

21.7 Operation Plan Evaluation

Each time IMACS finds an operation plan, it tests whether the plan can achieve the design tolerances. IMACS does this by estimating what tolerances each operation can achieve. Typical approaches for computer-aided tolerance charting are computationally very intensive and consider only limited types of tolerances. Thus, IMACS simply evaluates the manufacturability aspects of a wide variety of tolerances without getting into optimization aspects [254]. As an example, the operation plan shown in Figure 21.8 and Table 21.1 satisfies the tolerances shown in Figure 21.3 and thus is an acceptable way to make P_0 from S_0.

If the plan can achieve the design tolerances, then IMACS estimates the plan's manufacturing time. The total time of a machining operation consists of the cutting time (when the tool is actually engaged in machining) plus the noncutting time (tool-change time, setup time, etc.). Methods have been developed for estimating the fixed and variable costs of machining operations; our formulas for estimating these costs are based on standard handbooks related to machining economics, such as Winchell [554]. As an example, Table 21.2 shows the estimated production time for the operation plan shown in Figure 21.8 and Table 21.1.

21.8 Efficiency Considerations

As described by Gupta and Nau [254], IMACS uses a depth-first branch-and-bound search to generate and evaluate FBMs and plans one at a time. By evaluating them

Table 21.2 Estimated production time for the operation plan.

Operation	*Time (min)*	*Operation*	*Time (min)*
Drill h1	2.3	Mill s2	5.0
Drill h3	0.3	Mill s4	5.0
Drill h5	0.3	Mill s6	5.0
Drill h7	0.6	Mill s8	5.0
Drill h9	0.6	Mill s9	4.0
Drill h11	0.3	Mill s10	4.2
Drill h12	0.3	3 setups	6.0
Total time: 39 minutes			

as they are being generated and keeping track of the best one it has seen so far, IMACS can discard FBMs and plans that look unpromising, even before they have been fully generated. For example, from the 22 primary features (some of which are shown in Figure 21.6), one can form 512 FBMs for the socket P_0, but IMACS generates only 16 of these FBMs. Here are some of IMACS's pruning criteria, which can be thought of as similar to critics in HTN planning.

- IMACS discards an FBM if it contains features whose dimensions and tolerances appear unreasonable. Examples include a hole-drilling operation that has too large a length-to-diameter ratio; a recess-boring operation that has too large a ratio of outer diameter to inner diameter; and two concentric hole-drilling operations with tight concentricity tolerance and opposite approach directions.
- IMACS discards an FBM if it appears that there will be problems with workholding during some of the machining operations. Currently, IMACS's workholding analysis is based on the assumption that a flat-jaw vise is the only available fixturing device [138]. A more sophisticated fixturability analysis would also need to consider the use of other kinds of fixtures, such as vise clamping and toe clamping.
- IMACS computes a quick lower bound on the machining time required for an FBM or plan and discards the FBM or plan if this lower bound is above the time required by the best plan seen so far.

21.9 Concluding Remarks

IMACS was written as a prototype for research purposes, and its operation plans do not contain all of the information that would be needed for a manufacturing process plan. In particular, IMACS does not determine what fixtures to use to hold the part in place during each manufacturing operation, and it does not determine the trajectory to be followed by the cutting tool during the manufacturing operation. However, even without this information, operation plans of the kind produced by IMACS may still provide useful feedback to the designer about the manufacturability of the design and suggest ways to change the design in order to improve its manufacturability while still fulfilling the designer's intent. A way to do this is discussed by Das *et al.* [138].