ESTIMATION OF SETUP TIME FOR MACHINED PARTS: ACCOUNTING FOR WORK-HOLDING CONSTRAINTS USING A VISE

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ABSTRACT

For machined parts, setup time is a major component of the total time required to manufacture a machined part from a stock. If the number of setups and hence setup time can be reduced, this will not only decrease the manufacturing time, but will also ensure better machining accuracy, require fewer work-holding devices and increase machine usage time.

To achieve any improvement in setup time, first we need to estimate the setup time accurately. In this paper we propose a methodology to estimate the setup time for machining prismatic parts in a three axis vertical machining center. We concurrently consider three major factors for estimating the number of setups, namely—the precedence constraints among machining operations, the feasibility of work holding using vise clamping, and the availability of datum faces for locating the workpiece on the machine table during machining on a 3 axis vertical machining center.

1. INTRODUCTION

As design activities determine most of the life cycle cost of a product [18], early detection of any production related problem will save time and money in the long run. In particular, if the manufacturability of a part can be estimated early in the design stage, this can help in avoiding costly modifications to design later in the production cycle. The manufacturability of a machined part depends on many factors—but one of the biggest factors is the setup time. In general, reducing the number of setups will not only reduce the time needed for manufacturing, but will also result in better machining tolerances for the machined component.

To achieve any improvement in setup time, first we need to estimate the setup time accurately. This paper describes a methodology for estimating the setup time needed to machine a prismatic part in a three axis vertical machining center. The outline of the approach is shown in Figure 1. As shown in Figure 1, we examine different sets of machining features that can be used to create the part, and for each set of machining features we investigate different possible setup sequences. We use branch-and-bound techniques to avoid enumerating every possible combination of features and sequences.

The paper is organized as follows. Section 2 reviews related work. Section 3 describes the preliminary analysis performed in Step 1 of Figure 1. Section 4 describes how we generate FBMs in Step 2(a) of Figure 1, and Section 5 describes how we determine the setup time required for an FBM in Step 2(b) of Figure 1. Finally, Section 6 presents our conclusions and directions for future work.

2. REVIEW OF RELATED WORK

Section 2.1 presents some background work on how precedence constraints among features are identified and handled, and Section 2.2 gives reviews of some work on automated setup planning and fixturability analysis for machined parts.

2.1. Precedence Constraints

For a given part, the machining operations usually cannot be performed in any arbitrary order [7]. Geometric and technological constraints will require that certain operations be performed before or after other operations. These precedence constraints among machining operations play an important role in setup time estimation.

AMPS [3] uses heuristic techniques to determine precedence constraints among features. A number of rules based on machining practices have been defined and are used to determine precedence constraints among pairs of features. This approach allows for *strict* and *loose* constraints. Strict constraints cannot be violated, while loose constraints can—but at a detriment to ensuring good machining practice. The machining features in this approach are allowed to have multiple approach directions and may have conditional precedence constraints.

The Machinist system [10] is capable of handling the precedences that arise because of setup considerations. In this system, precedences are generated by examining the setup interactions among machining features. If machining of a feature destroys the precondition for clamping during machining of another feature, then these two features interact and a precedence constraint exists between them.

Because of its closeness to well-known combinatorial optimization problems, optimization of operation sequences has received significant research attention. A number of systems have been developed that take precedence constraints

1. **Preliminary Analysis.**
    (a) As input, obtain CAD models of the part P and the stock S. Find all primary machining features for P and S, and let $\mathcal{F}$ be the set of all of these features, as described in Section 3.1.
    (b) Find constraints on the order in which the features in $\mathcal{F}$ can be machined, as described in Section 3.2.
2. **Estimation of Setup Time.** Perform the following steps repeatedly, until all the promising FBMs have been considered (an FBM is a set of features $F \subseteq \mathcal{F}$ that contains no redundant features and is sufficient to create P from S).
    (a) As described in Section 4, generate a promising FBM. (An FBM is considered unpromising—and thus is discarded—if a quick analysis of its approach directions reveals that it will require a greater setup time than the best FBM seen so far. Since we build up FBMs one feature at a time, we can often detect this before the FBM is fully generated.)
    (b) Estimate the FBM's setup time by generating and examining possible setup sequences for its features, taking into account the following factors in a concurrent manner:
        - approach directions and precedence as described in Section 5.1;
        - how the workpiece can be probed for locating it on the machine table, as described in Section 5.2;
        - how the workpiece can be held properly for machining, as described in Section 5.3.

    In order to achieve efficient computation, this step uses branch and bound techniques that enable it to discard unpromising setup sequences before they are fully generated.

Figure 1: The basic steps of our approach for estimating setup time.

as input and find the optimum operation sequence [14, 15]. However, most of these systems do not automatically generate the complete set of precedence constraints.

Gupta *at al.* [6] provide a systematic method of finding precedence constraints among machining operations which considers dimensional and geometric tolerances, accessibility of machining features, standard machining practices and machining time.

2.2. Fixturability and Setup Planning

To ensure successful machining, each intermediate workpiece shape should be fixturable. This requires consideration of fixturing devices and formulating the conditions that are needed to insure proper fixturing. Setup planning involves determining the various setups in which the part will be machined. While advances have been made in automated fixture design, existing research has mainly focused on designing new fixtures for a given geometry.

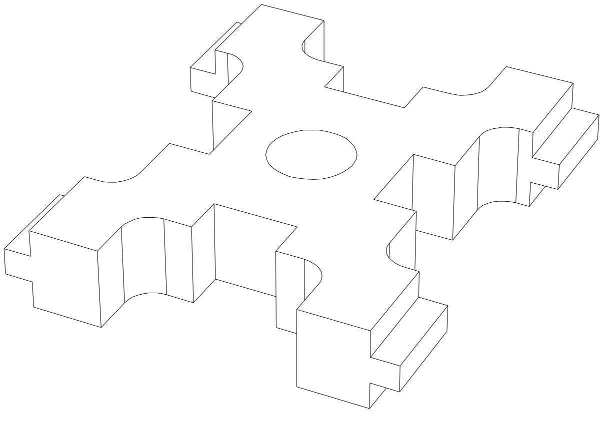
Chang [3] presented comprehensive conditions for holding the workpiece in a vise. These conditions are based on the intermediate workpiece geometry and are sufficient for successfully clamping the workpiece. He also presented an algorithm for setup planning that, while producing valid results, in certain cases may generate setup plans that are non-optimal.

Kumar *et al.* [12] presented a system for automated fixture design system. They used different supporting, locating and clamping constraints as rules. It appears that there can be a very high number of possible combinations of locations for the elements. It is not clear from their presentation how they exactly determine the locations of different fixturing elements on the part. They also did not include most of the types of precedence constraints among features in their work.

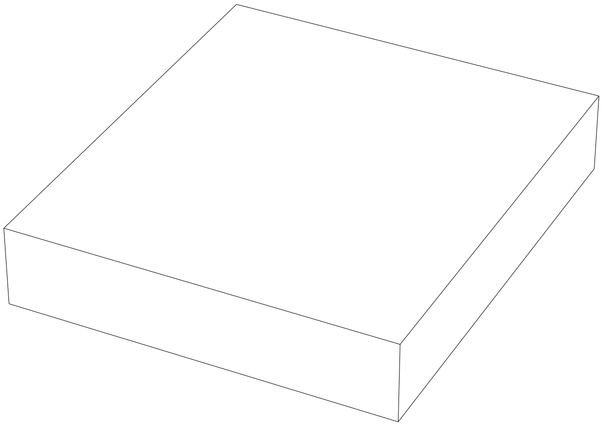
Sakurai [17] developed and implemented a methodology for automatic setup planning and fixture design. He developed some guidelines for selecting and locating clamps and locators. He considered both vertical and horizontal clamping. He also mentioned that under certain cases these guidelines are prone to failure. He also uses some kinematic and friction force analysis for validating the locations of clamps.

Yue and Murray [21] presented a comprehensive set of fixturability and clamping conditions for vise clamping, machine table clamping, and frame bolting for manufacture of 2.5D prismatic parts. These conditions are based on intermediate workpiece geometry and consider friction forces. Lee and Cutkosky [13] provide a detailed analysis of friction force estimation for fixtures. For a review of fixture design automation, readers are referred to [9, 19].

As pointed out by Chang [2], in most approaches for setup planning and fixture design, the two tasks are done sequentially: first a set of machining operations are found which would be machined in a setup and then fixture planning is performed. In contrast, our approach addresses the two tasks concurrently: although we do not perform detailed fixture design, we check for the feasibility of fixturing when we generate the sequence of machining operations.



(a): An example part



(b): The stock

Figure 2: An example part, which we will call P1 and the stock from which it is machined.

3. PRELIMINARY ANALYSIS

3.1. Input from the Designer

A *part*, P, is the final component created by executing a set of machining operations on a piece of *stock*, S. In this paper, we assume that P and S are available as solid models. For example, Figure 2(a) shows an example part which we will call P1; this part would typically be machined from a rectangular piece of stock S1 (shown in Figure 2(b)).

A *workpiece* is the intermediate object produced by performing zero or more of the operations needed to create P. A *machining feature* is a portion of the workpiece affected by a particular machining operation. A machining feature consists of three components: the volume swept by the tool, the *approach direction* (the direction from which the operation is performed), and the type of operation. Only a portion of the swept volume actually corresponds to the volume that can be removed by the machining feature. We refer to this volume as *removal volume* $\mathrm{rem}(f)$. The effective removal volume of a feature with respect to the stock is the intersection of the removal volume with the stock. The *accessibility volume*, $\mathrm{acc}(f)$, is the remaining portion of the tool swept volume. An approach face separates the removal volume from the accessibility volume.

In this paper, the only types of operations we will consider are end milling, side milling, and drilling performed in a vertical machining center. Each machining operation is capable of creating certain types of surfaces: drilling produces cylindrical and conical surfaces, and end milling and side milling produce planar and cylindrical surfaces. The basic three types of machining features used in this paper are shown in Figure 3. In Figure 3(b) the pocket is the removal volume for the end milling feature. The top plane of the workpiece is the approach face and accessibility volume lies above that plane.

A *primary* feature for a given part P and stock S is a machining feature that is minimal with respect to S and maximal with respect to P. Figure 4 shows an example; for a detailed definition the reader is referred to [6, 8].

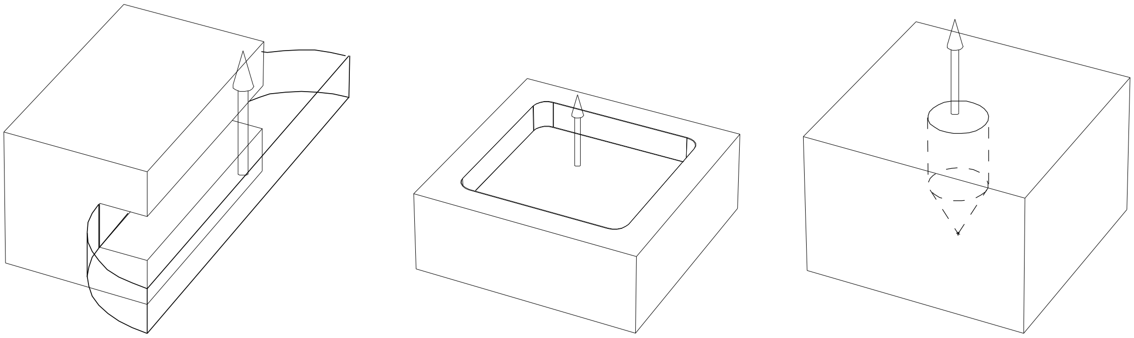
Given a part P and stock S, we will let $\mathcal{F}$ denote the set of *all* primary features for P and S. In [5, 16], we describe an algorithm that, given P and S, will automatically find $\mathcal{F}$. For example, in the case of the part P1 and stock S1 shown in Figure 2, $\mathcal{F}$ contains 30 machining features, some of which are shown in Figure 5. In particular, $h1$ is drilling features and $s1$ through $s12$ are end-milling features.

3.2. Precedence Constraints

Due to various types of interactions among the features used to machine a part, the features cannot be machined in any arbitrary order. Instead, these interactions introduce precedence constraints requiring that some features be machined before or after other features. For example, Figure 6(a) shows a part in which the slot-hole interactions create precedence constraints for machining of that part. For proper drill engagement, the large vertical hole d1 must precede the two end-mill features s1 and s2. Also, to get flat entry and exit faces while machining the drilling feature d2, the horizontal hole d2 must precede the end-milling features s3 and s4. These precedence constraints are shown in Figure 6(b).

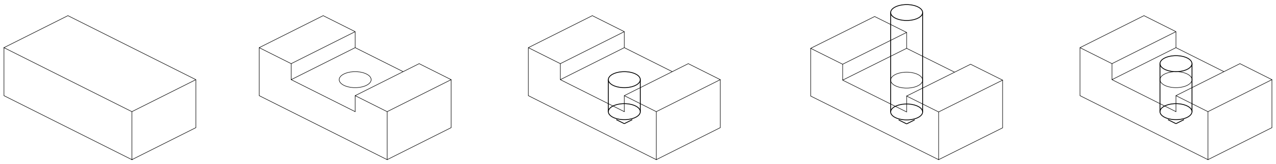
More generally, we consider precedence constraints coming from accessibility considerations and from preferred manufacturing practices (such as those enumerated in [1, 3]). Here are some examples:

1. If the accessibility volume of a feature f' intersects with the removal volume of feature f, then f has to be machined before f'.
2. Suppose f is an end-milling feature with at least one side open (so that it can be created without first drilling a hole to allow entry of the end-milling tool), and f' is a drilling feature whose removal volume intersects with the removal volume of f. If the profile of f' is contained in the profile of f, then f should be machined before f'; otherwise f' should be machined before f. Similar



(a): Side milling feature (b): End milling feature (c): Drilling feature

Figure 3: Examples of machining features.



(a): stock S

(b): part P

(c): non-primary, because hole not maximal with respect to the part

(d): non-primary, because hole not minimal with respect to the stock

(e): primary

Figure 4: Example of primary and non-primary features.

precedence constraints hold between side milling and drilling features.

3. If two drilling features f and f' are collinear and their removal volumes intersect, then the smaller one should be drilled first.

We are interested in finding these precedence constraints because the number of setups (and hence setup time) required to machine the part will depend on them (see Section 5). The procedure to find the precedence constraints is straightforward: we simply check, for each pair of features which intersect volumetrically and do not have the same removal volume with respect to the stock, whether the above conditions hold. If two features have the same removal volume, then we do not need to consider precedences between them, because no plan for manufacturing the part will involve machining both of these features.

4. GENERATION AND EVALUATION OF FBMS

A *Feature Based Model* (FBM) for P is any irredundant subset $F \subseteq \mathcal{F}$ such that P can be produced from S by removing the features in F. For example, Figure 5 shows one of the FBMs for the part P1. In general, a single part may have several different FBMs, and thus there may be several different ways to machine the part.

The number of FBMs for a part can be very high—for example, the part shown in Figure 2 has 512 different FBMs without even considering the side milling operations. In order to find the FBMs that has the least setup time without having to generate all of the FBMs, we use a depth-first branch-and-bound procedure that builds each FBM one feature at a time. Different kinds of heuristics can be applied while building the FBMs to reduce the number of FBMs need to be generated even further, Gupta [8] discusses these heuristics in detail in his PhD thesis. As the FBM is being built, we discard it before it has been fully generated if our analysis reveals that it will have a high setup cost than any other FBM already built and examined.

The procedure Analyze-Design take as arguments the part P, the stock S, the set of all possible primary machining features $\mathcal{F}$, a partial FBM G (which is initially empty) and the setup time T (which is initially ∞). Each time that Analyze-Design finds an FBM that has lower setup time than T, it updates T accordingly.

In Analyze-Design and several of its subroutines, t_s is the setup time required for each setup. In this paper, t_s is the setup time for a flat jaw vise, which we take to be 2 minutes [20].

After completion of Analyze-Design, T is the minimum setup time over all of the FBMs. If $T = \infty$ after completion of Analyze-Design, then there is no way to manufacture the part P using the manufacturing operations that we are considering in this paper (drilling and milling operations on a three-axis vertical machining center using vise-clamping for fixturing). One has to consider different types of manufacturing and work-holding procedure to manufacture that part.

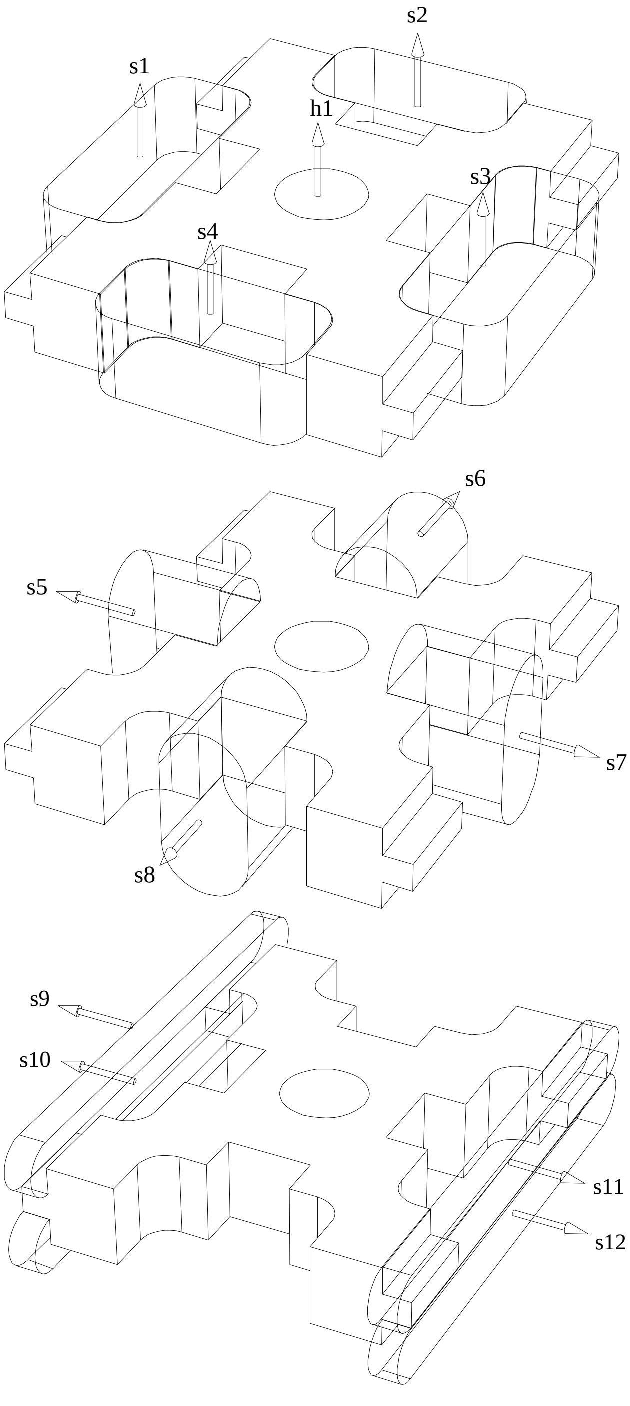


Figure 5: An FBM for the part P1

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procedure ANALYZE-DESIGN($P, S, \mathcal{F}, G, T$)
  1. Let $n$ be the number of approach directions of the features in $G$, and $t_s$ be the setup time for each setup as described in the text. If $n \times t_s \geq T$, then return $T$, because $G$ will not result in an FBM with lower setup time than $T$.
  2. Otherwise, if there exists any feature $g \in G$ such that the removal volume of $g$ is completely subsumed by the union of the removal volumes of the other features in $G$, then return $T$ because $G$ is redundant.
  3. Otherwise, if subtracting the features in $G$ from the stock $S$ creates the part $P$, then $G$ is an FBM. To find the setup time for that FBM, do the following:
      (a) Set $F = G$
      (b) $T = \min(T, \text{FIND-BEST-SETUP-TIME}(F, G, C, \infty, 0))$
          (As described in Section 5.1, FIND-BEST-SETUP-TIME finds the machining sequence for the FBM $G$ that requires the least setup time.)
      (c) Return $T$
  4. Otherwise, do the following:
      (a) Pick a feature $g$ from $\mathcal{F}$
      (b) $T = \min(T, \text{ANALYZE-DESIGN}(P, S, \mathcal{F} - g, G \cup g, T))$
          $T = \min(T, \text{ANALYZE-DESIGN}(P, S, \mathcal{F} - g, G, T))$
      (c) Return $T$
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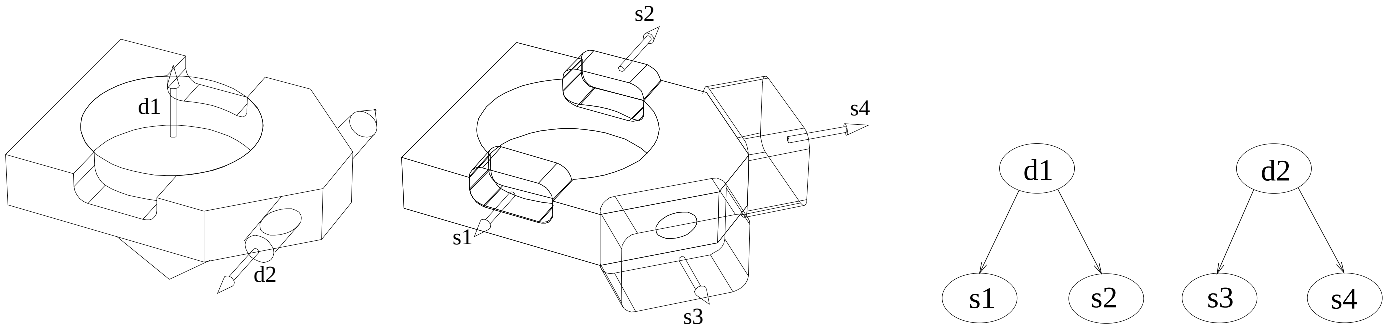
5. SETUP-TIME ESTIMATION

It is evident that in a 3-axis vertical machining center, only features with same approach direction can be machined in one setup. In this paper, we consider three more criteria for determining whether a set of features having the same approach direction can be machined in the same setup. First, the precedence features of those either have to be already machined or the precedence features have to belong to the same set. Second, it should be possible to probe the workpiece for locating on a CNC machining center. Third, it should be possible to hold the workpiece using vise in such a way that the work holding devices do not interfere with the features to be machined. We have already discussed precedence constraints in Section 3.2. We will discuss the probing and fixturing considerations respectively in Sections 5.2 and 5.3.

Unlike other approaches discussed in Section 2, we do not find the operation sequence first and then analyze fixturability. We take the fixturability and probing feasibility



(a): A part in which some of the features must be machined before others

(b): Precedence constraints among the features in (a)

Figure 6: Example of precedence constraints.

into consideration while generating the setup sequence itself. This concurrent approach ensures that we never generate a setup sequence for which intermediate workpieces cannot be held using a vise. In this fashion we integrate the setup planning and fixturing planning as one step. Although individual aspects of setup planning and fixture design automation had been accomplished by others, our approach combines the two in one framework.

Once we have an FBM, it is a specific set of machining features all of which needs to be machined to get the final part from the stock. Each feature f has a specific approach direction $\vec{v}(f)$, and some of these features may have some precedence constraints among them. Each operation sequence for machining the part corresponds to a sequential ordering $\{f_1, f_2, \ldots, f_m\}$ of the features that is consistent with the precedence constraints. In a vertical machining center, the number of setups required by this operation sequence is one more than the number of times the approach direction or the vise position changes when we scan the sequence from start to finish.

The number of setups needed to machine the FBM will be the minimum, over all feature machining sequences satisfying the precedence and work-holding constraints of the number of setups required by the feature machining sequence. Estimation of setup time involves determining the exact setup sequence and estimating the time associated with each of the setups in the sequence. Thus, the formula for setup time estimation is given by

$$\text{setup time } = \sum_{i=1}^{n} t_{si}$$

where t_{si} is the time associated with the i^{th} setup. The actual value of t_{si} depends on the part size, weight, geometry and the setup method. Wilson's handbook [20] gives data for a variety of setup procedures. We assume that the parts are small in size which can be moved and reoriented manually by one person during the machining process. In particular, since we are assuming that vise clamping is the only work holding method available, we use $t_{si} = t_s = 2$ minutes for every setup.

The FBM F with the set of precedence constraints C can together be seen as a machining plan. It should be noted that given F and C, the minimum number of setups is not necessarily equal to the number of approach directions. In presence of precedence constraints, the minimum number of setups for a given machining plan may be greater than the number of approach directions. Also in some situations the number of setups will be affected by the probing and fixturing feasibility considerations.

5.1. Algorithm for Setup Time Estimation

The procedure Find-Best-Setup-Time described below estimates the minimum setup time required to machine a given FBM F. Find-Best-Setup-Time is a branch and bound procedure which in turn calls the procedures Workpiece-Probe and Holding-Analysis. The procedure Workpiece-Probe finds whether it is possible to properly locate an intermediate workpiece using machine mounted probes. The procedure Holding-Analysis analyses the feasibility of machining a collection of machining features in a setup using vise as workholding device.

The procedure Find-Best-Setup-Time takes as argument a set of features B which are to be put in valid setups, the set of precedence constraints among the features in B and the setup time t. Another argument F is the FBM for which setup time is being estimated, this remains unaltered during the execution of the procedure. Initially the set of features is the FBM G found by the procedure Find-FBM and the setup time is zero. The argument T (initially ∞) is used by Find-Best-Setup-Time to hold the best setup time it has seen in any of the setup sequences it has explored so far.

Find-Best-Setup-Time returns the best setup time it can find for the FBM G. If Find-Best-Setup-Time returns ∞, then this indicates that the FBM is not manufacturable using the manufacturing operations that we are considering in this paper (drilling and milling operations on a three-axis vertical machining center using vise-clamping for fixturing).

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procedure Find-Best-Setup-Time($F, B, C, T, t$)
  1. If $t \geq T$, then return $T$, because the setup time is not better than the best solution so far. This condition prevents unpromising setup sequences from being investigated further.
  2. If $B = \emptyset$, then there are no remaining features, so return $t$. Otherwise, do the steps below.
  3. Let READY be the set of all features in $B$ that have no predecessors.
  4. Let $V$ be the set of all approach directions of features in READY (i.e., $V = \{\vec{v}(f) : f \in \mathrm{READY}\}$). $V$ contains the approach directions from which the next setup can be machined.
  5. For every approach direction $\vec{v} \in V$, do the following:[1]
     (a) Let $H$ be the set of all features $f \in B$ such that
         i. $f$ has $\vec{v}$ as its approach direction;
         ii. either $f$ has no predecessor in $B$, or all predecessors in $B$ have $\vec{v}$ as their approach direction.
         Note that all of these features can be machined in the same setup if the fixturability conditions permit.
     (b) Let $W = S -^* ((\cup^* F) -^* (\cup^* B))$.
         $W$ represents the current workpiece, i.e., the workpiece after machining the features already removed from $B$ during its recursive calling sequence (see Step 5(c)ii below).
     (c) If Workpiece-Probe($W, \vec{v}$), then
         i. $\mathcal{K}$ =Holding-Analysis($W, \vec{v}, H, C$)
            (Each element of the set $\mathcal{K}$ returned by Holding-Analysis is a set of features $K \subseteq H$ that can be machined in one setup.)
         ii. Remove from $\mathcal{K}$ any set $K'$ that is a proper subset of some other set $K \in \mathcal{K}$
             For each $K \in \mathcal{K}$,[2]
                 $T = \min(T,$ Find-Best-Setup-Time$(F, B - K, C - C', T, t + t_s))$,
                 where $C'$ is the set of all precedence constraints in $C$ that involve at least one feature in $K$.
             Return $T$
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In step 5c of the procedure Find-Best-Setup-Time we check the workpiece geometry to find if it has faces and features which allow locating the workpiece on a CNC machining center. We proceed with the workholding analysis only if the workpiece has that property, otherwise a different setup sequence is chosen for analysis.

In Step 5(c)i, Find-Best-Setup-Time uses a procedure called Holding-Analysis (described in Section 5.3.1) to find alternative sets of features that can be machined in one setup. Holding-Analysis assumes that a vise is the only available fixturing device—but we are developing procedures for use with other types of work holding devices (such as clamping), and we intend to use these procedures to augment the set $\mathcal{K}$. Since Holding-Analysis assesses fixturability independent of the rest of the analysis, it will be straightforward to incorporate these procedures into our approach.

Here is as an example how Find-Best-Setup-Time works. For the part P1 shown in Figure 2, the FBM that requires the least number of setups is shown in Figure 5. In this FBM, the features $s1, s2, s3, s4$ and $h1$ all have same approach direction and do not have any precedence constraints. If there are no problems from work holding point of view, all these can be machined in one setup. However, no face pairs exist to hold the workpiece in such a manner so that all these features can be machined in one setup. So these features will have to be machined in two setups. By means of this and similar analysis of the other features, Find-Best-Setup-Time will find that this FBM requires at least six setups.

5.2. Probing methodology

Whenever we have a possible workpiece to investigate for viability of a setup, we need to find whether there exists geometric features on the workpiece which can be used to establish a datum on the part for CNC machining. If that is not possible we will discard any setup sequence which will require us to machine that workpiece from the given direction. Kanumury *et al.* gave details about the need and procedure of probing in their article [11].

At Step 5c of the procedure Find-Best-Setup-Time described in Section 5.1 we check the workpiece for feasibility of probing it for locating on a machine table. The procedure Workpiece-Probe returns true if it is feasible to probe the workpiece and returns false otherwise. The feasibility is determined by checking for the existence of already machined faces or stock faces which are accessible from the top, in the workpiece that allow establishing a datum point for machining the features. We assume that existence of three mutually perpendicular planar faces, one of which is perpendicular to the approach direction is sufficient for establishing datum.[3]

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[1] We pick the approach directions to examine in decreasing order of the number of features in READY from that approach direction

[2] For computational efficiency, we pick K in decreasing order of cardinality among all the $K \in \mathcal{K}$

[3] It is possible to establish a datum with combinations of cylindrical and planar faces in some special cases, we intend to extend our approach to account for those cases in future.

5.3. Work Holding Analysis

We assume that only flat jaw vise is used for holding the workpiece during machining. A vise is a pair of rectangular jaws. The workpiece needs to be secured by putting two vise jaws agaqinst two parallel faces on the workpiece. For properly holding the workpiece the minimum projected area of those two parallel faces between the jaws have to be more than a specific minimum area.

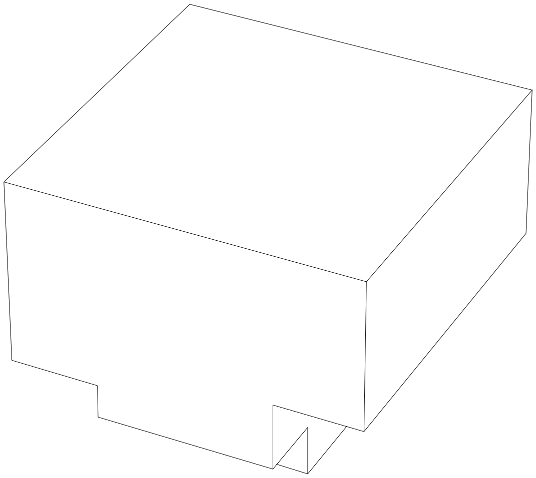
In the following Section 5.3.1, we describe the details of how the work holding analysis works. We do not suggest the exact setup locations for different setups. We only determine which features can be machined in one setup using vise jaws as work holding device.

5.3.1. Analysis for Vise Clamping. This section describes the Holding-Analysis procedure that is used in Step 5(c)i of the procedure Find-Best-Setup-Time. For this analysis the workpiece is oriented to have the features in set H facing upwards with their approach direction $\vec{v}$ perpendicular to the machine table. It is also assumed that the workpiece is kept at a fixed position on the machine table and the vise jaws are moved around to hold the workpiece. During setting up of a workpiece on the machine table for actual machining on the shop floor, usually the vise is kept at a fixed position and the workpiece is reoriented. However for automated fixturability analysis purpose the relative position between the workpiece and the vise is of real importance and so our assumption will not produce incorrect results.

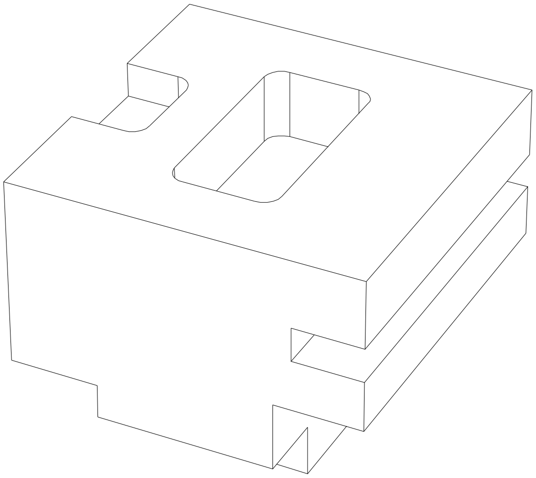
The procedure Holding-Analysis takes as argument the current workpiece W, the set of features under consideration H, the approach direction $\vec{v}$ for the features in H and the precedence constraints among the features. First it finds out the face pairs (Z) which can be used to hold the workpiece which are parallel to each other, is accessible to the vise jaws and has a minimum projection area on each other A_t. The value of this threshold minimum area A_t depends on the cutting force required to machine the part. We will assume direct relation between the minimum threshold area and the material removal rate (MRR) of the machine tool. For the purpose of analysis we will take MRR to be the maximum possible material removal rate of the machine tool in use. The procedure calculates the set of distances (Γ) of the features which might possibly intersect with the vise jaws, from a plane λ tangent to the bottom of the workpiece (for example, Figure 9 and 8 show how this is done for the workpiece shown in Figure 7).

After calculating this set Γ, the procedure Holding-Analysis calls the procedure Find-Features-in-Setup which takes as argument the approach direction $(\vec{v})$, the workpiece (W), the set of features (H) under consideration and the sets of pairs of holding faces (Z) and the set Γ. It also takes as argument the set of precedence constraints among the features in H, C. It returns the set $\mathcal{K}$, which contains subsets of H which can be machined in one setup.

The set of vertical distances Γ are the vertical locations at which the tops of the vise jaws will be aligned with the parallel faces to test for interference with workpiece and the features. Later we also find similar lateral locations to align

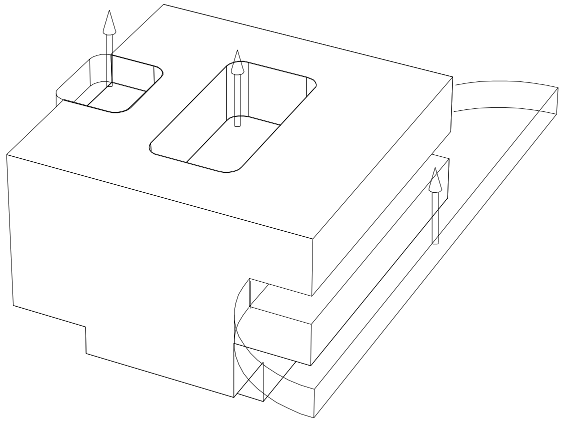


(a): Workpiece

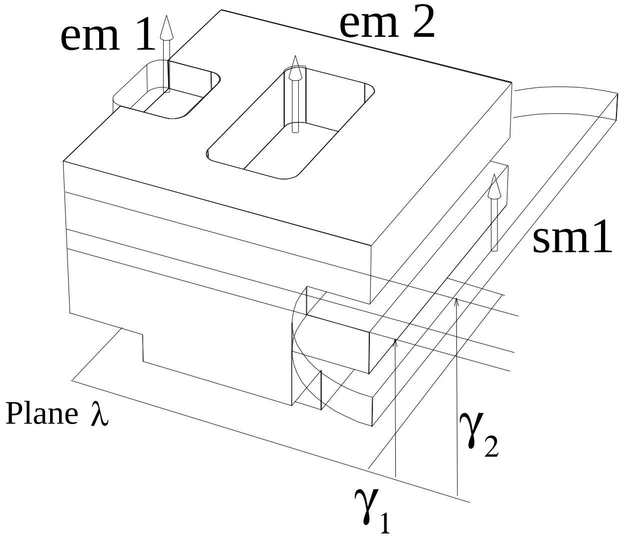


(b): Workpiece after machining features

Figure 7: Workpiece for Holding Analysis



(a) : Features to be machined



(b): Feature Heights

Figure 8: Diagram for holding analysis - I

the jaws. These locations may not be the best locations for actual fixturing but these are the locations where potentially maximum number of features will be available for machining.

```
procedure HOLDING-ANALYSIS($W, \vec{v}, H, C$)
  1. Let $R$ be the set of all planar faces in $W$ such that for
     each $r \in R$, $r$ is accessible to the vise jaw from the
     direction opposite to its face normal i.e.
       (a) $L \cap^* W = \emptyset$, where $L$ is the swept volume produced
           by sweeping $r$ infinitely in the direction of its face normal
       (b) $r$ is accessible from the direction opposite to the
           approach direction $\vec{v}$
     (Thus $R$ is the set of all faces that can potentially be used as
     holding faces. For example, for the workpiece shown in Figure 7,
     $R$ consists of the faces a1,a2,a3,b1,b2,c1,c2 shown in Figure 9).
  2. Let $\lambda$ be the plane touching the workpiece $W$ which is
     perpendicular to the approach direction $\vec{v}$ and tangent
     to the bottom of the workpiece.
     (For example see Figure 8)
  3. Let $Z$ be the set of all face pairs $(p_i, p_j) \in R$ such that
       (a) $p_i, p_j$ are parallel
       (b) The face normals of $p_i$ and $p_j$ have opposite direction.
       (c) $A \geq A_t$
           where $A$ is the area of the projection of $p_i$ on $p_j$ and
           $A_t$ is the minimum holding area for vise clamping
           (The set $Z$ will contain candidate face pairs which can be used
           for clamping in vise in a stable manner. For example, in the case
           of the faces shown in Figure 9, $Z$ would contain the face pairs
           (a1,a2),(b1,b2),(c1,c2) but would not contain (a1,a3), because
           the area of projection of a1 on a3 is less than $A_t$.)
  4. For each $h \in H$ which intersects with any face in the set of face
     pairs $Z$, let $\gamma_h$ be the minimum distance from $\lambda$ to the
     feature $h$, measured along the approach direction $\vec{v}$
  5. Let $\Gamma$ be the set of all the $\gamma_h$'s
  6. $\mathcal{K} =$
     FIND-FEATURES-IN-SETUP($\lambda, \Gamma, \vec{v}, W, H, Z, C$)
  7. Return $\mathcal{K}$
```

Figure 8(a) shows three features on a workpiece which can be machined in one setup if no fixturing problems exist. Figure 8(b) shows the plane λ and the distances γ from the that plane to the features. Note that the distance to feature *em 2* from the bottom plane is not computed, because in this orientation *em 2* is not going to interfere with the vise jaws for any of the face pairs in Z.

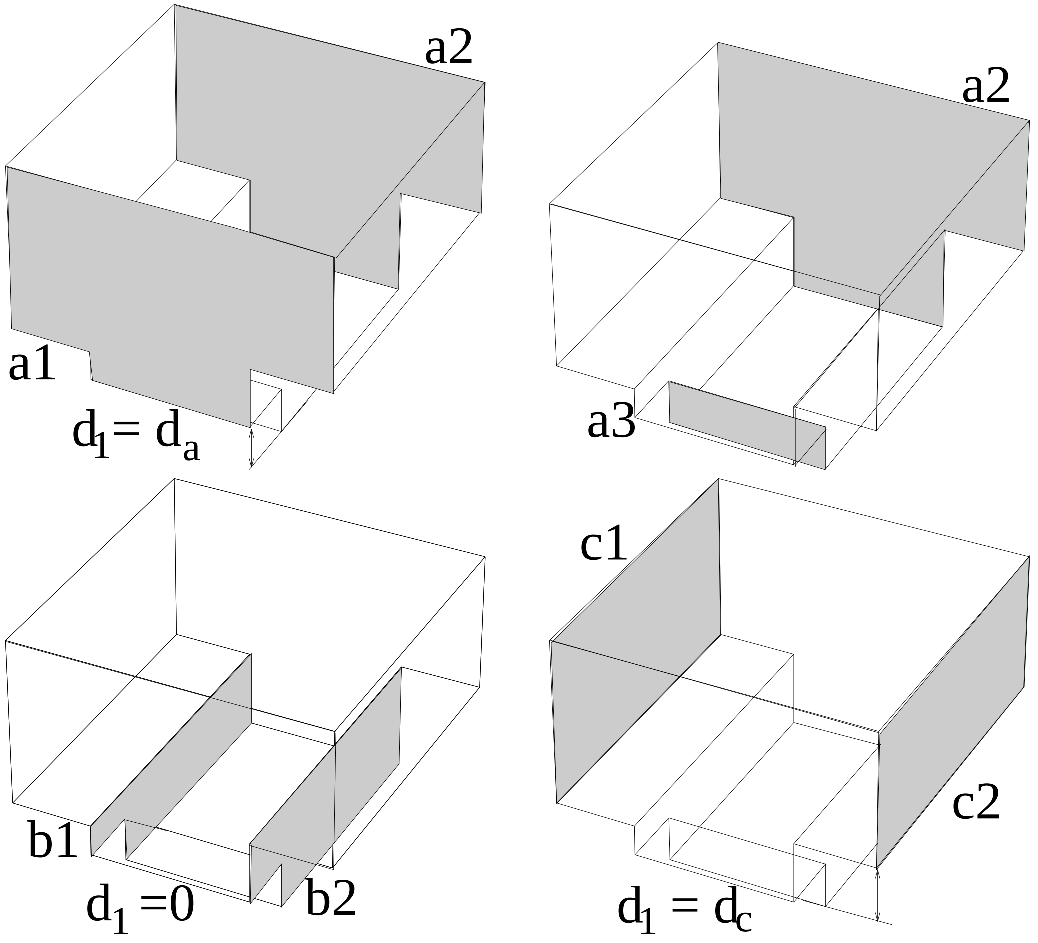


Figure 9: Diagram for holding Analysis -II

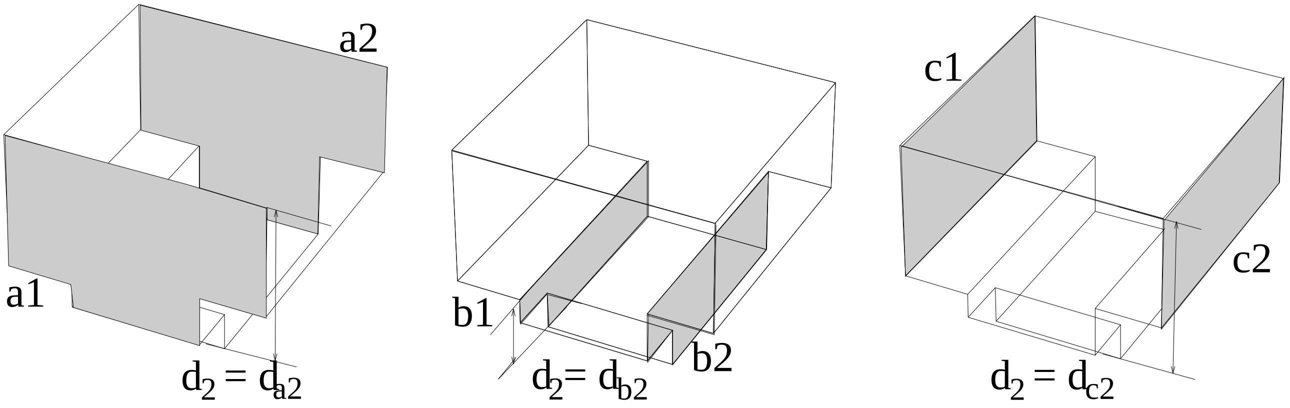


Figure 10: Diagram for holding analysis - III

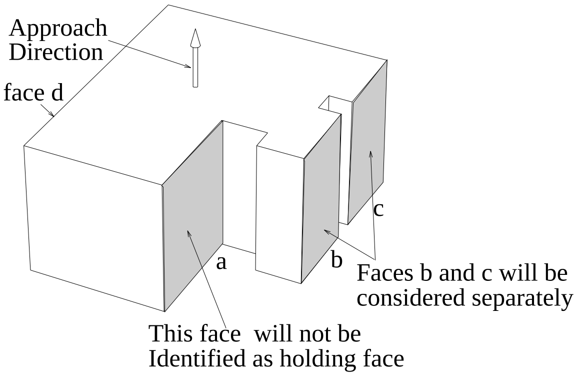


Figure 11: Cases where the algorithm does not detect possible holding faces

The procedure HOLDING-ANALYSIS is *sound*, in the sense that it will only find the face pairs which will allow proper work holding. However, it will fail to identify some possible faces and face pairs which could have been used for the clamping purpose. Figure 11 shows both of those situations. These cases are:

1. Some faces which are only partially accessible can be used as holding face, but this procedure will reject those as holding faces. (The face a in Figure 11)
2. Some times different faces on the same plane can be used together for holding the workpiece, but this algorithm does not consider that. (The faces b & c with respect to face d in Figure 11)

For the purpose of analyzing how to put features in one setup we assume the vise to be a pair of two identical rectangular solids J_1 and J_2. The length of these jaws are more than the longest linear dimension of the workpiece W measured along the face normals of all the faces $r \in R$. The height of the vise jaws is more than the longest linear dimension of the workpiece W measured in a direction parallel to $\vec{v}$ along all $r \in R$. The width of the jaws is not of consequence to the analysis. For the sake of completeness we assume both the jaws to have the same unit width. We assume that the opening between the vise jaws is sufficient to cover the distance between any pair of faces in Z. The two vise jaws will be aligned with the faces of the set of face pairs Z along the length of the jaws at different locations for finding which features can be machined in one setup. We also assume that both the jaws have to be in the same vertical and longitudinal position during a setup.

The conditions checked by the procedure FIND-FEATURES-IN-SETUP for a subset of features in H to be machinable in one setup are the following:

1. The vise jaws will not intersect with the features removal or accessibility volume
2. All the precedence(s) of the features in that subset also have to belong to that subset.

```
procedure FIND-FEATURES-IN-SETUP($\lambda, \Gamma, \vec{v}, W, H, Z, C$)
  1. (Below, we compute sets $K_L$ and $K_R$ of features which can be machined in one setup using the face pair for holding the workpiece with the vise jaw $J_2$ respectively to the left and right of the face $p_j$.)
     Initially, set $K_L = K_R = \emptyset$
  2. For each face pair $(p_i, p_j) \in Z$ (in increasing order of the total area of intersection with features in $H$, in case of more than one face pair having the same area of intersection with features, the one with a face of higher overall area will be selected), do the following:
     (a) Let $d_1$ and $d_2$ be the shortest and longest distance from $\lambda$ to any point in $A$, where $A$ is the area of projection of $p_i$ on $p_j$ (see Figure 9 and 10)
     (b) Let $\Gamma_s = \{d_2\} \cup \{d \in \Gamma : d_1 < d < d_2\}$
         (The set $\Gamma_s$ contains the possible vertical locations where the face pair might potentially be aligned with the top of the vise jaws.)
     (c) (Below, we compute sets $K_L^*$ and $K_R^*$ of features which can be machined in one setup using the face pair for holding the workpiece with the vise jaw $J_2$ respectively to the left and right of the face $p_j$ at the vertical position $\gamma$ of the workpiece.)
         Initially, set $K_L^* = K_R^* = \emptyset$
     (d) For each $\gamma \in \Gamma_s$ do the following in the order of increasing value of $\gamma$ (the higher the value of $\gamma$, the higher the portion of the workpiece located inside the vise jaws):
         i. If the area of the projection $A$ of face $p_i$ on $p_j$ below the height $\gamma$ is less than $A_t$, then exit, because there is not enough holding area to hold the workpiece securely in the vise. Otherwise, do the following:
         ii. If $K_L^* = \emptyset$ then
                 $K_L^* =$
                 LEFT-ANALYSIS($W, H, A, A_t, C, \gamma$)
                 $K_L = K_L \cup K_L^*$
                 If $K_L^* = H$, then then set $\mathcal{K} = H$ and go to Step 4, because we found that all the features can be machined in one setup and we need not search any more.
             If $K_R^* = \emptyset$ then
                 $K_R^* =$
                 RIGHT-ANALYSIS($W, H, A, A_t, C, \gamma$)
                 $K_R = K_R \cup K_R^*$
                 If $K_R^* = H$, then set $\mathcal{K} = H$ and go to Step 4, because we found that all the features can be machined in one setup and we need not search any more.
             (If $K_L^*$ or $K_R^*$ is non-empty then we need not call LEFT-ANALYSIS or RIGHT-ANALYSIS, respectively, because no more features will be accessible than before.)
  3. $\mathcal{K} = K_L \cup K_R$
```

4. Return $\mathcal{K}$

As an example, for the workpiece shown in Figure 7, the input parameter Z to FIND-FEATURES-IN-SETUP consists of three face pairs (a1,a2), (b1,b2) & (c1,c2) that can possibly be used for aligning the vise jaws. Figures 8,9 and 10 show the parameters used and calculated by FIND-FEATURES-IN-SETUP. As the face pair (a1,a2) does not intersect with any features and has the maximum area that will be considered first by FIND-FEATURES-IN-SETUP. For this face pair, $\Gamma_s = \{\gamma_1, \gamma_2, d_{a2}\}$. For face pair (c1,c2), $\Gamma_s = \{\gamma_1, \gamma_2, d_{c2}\}$. For the face pair (b1,b2), Γ_s will consist of only d_{b2}, as all the values in Γ are more than d_{b2}. FIND-FEATURES-IN-SETUP will not examine all of these face pairs, because all three features are accessible using the face pair (a1,a2).

The procedures LEFT-ANALYSIS and RIGHT-ANALYSIS analyze a face pair, their projection area on each other and the vise jaws to find the features accessible in different vise positions with respect to the workpiece. In both of these procedures we locate the workpiece with respect to the vise at different vertical positions and at the extreme lateral positions, (left and right), such that the minimum area of contact of the vise jaws with the faces being considered is the minimum threshold area A_t. These procedures compute the feature sets which can be machined in those locations.

In these procedures, we assume that appropriate spacer bars are available to position the workpiece at any desired height with respect to the vise jaws. As we are not trying to determine the exact location of the vise, but only finding which features can be machined in a setup, this assumption will not produce an incorrect result.

```
procedure LEFT-ANALYSIS($W, H, A, A_t, C, \gamma$)
  1. Let $L$ be a vertical line on the area $A$, such that the area of the patch on $A$ below the height $\gamma$ and left of $L$ is $A_t$[4]
  2. Let $J_2$ be a vise jaw (as described in the text) such that $J_2$'s inside face (the one facing the workpiece) lies on the face $p_j$, $J_2$'s top edge is at a height $\gamma$ on the face $p_j$, and $J_2$'s rightmost vertical inside edge is collinear with $L$.
  3. Let $J_1$ be a vise jaw whose inside face is at the corresponding location on $p_i$.
  4. If the jaws $J_1$ and $J_2$ intersect with the workpiece $W$, then return $\emptyset$ because the workpiece cannot be properly held at that position
  5. Otherwise, find the set of features $K^* \subseteq H$ which are accessible for machining at that location
     If $K^*$ contains any feature $k'$ such that the precedence of $k'$ is not in $K^*$, then $K^* = K^* - k'$
  6. Return $K^*$
```

RIGHT-ANALYSIS is an identical procedure where we place the vise jaw to the right of the workpiece instead of to the left of the workpiece as done in procedure LEFT-ANALYSIS. We do not suggest the vertical and lateral locations where we locate the workpiece with respect to the vise to be the ideal location for clamping. We choose these locations, because we can estimate the maximum number of features which might be accessible for machining by checking at those locations.

6. CONCLUSIONS AND FUTURE WORK

In this paper we present a methodology for estimating setup time for parts to be machined in a 3 axis vertical CNC machining center. Our approach is based on interpreting the part as a collection of machining features that correspond to all of the alternative ways in which the part can be machined. In order to generate groups of machining features that can potentially be machined in one setup, we consider the approach directions of the machining features, and precedence constraints among these features. We then examine these groups of features further, by considering the availability of probing faces in order to locate the workpiece during machining and whether there is a feasible way to hold the workpiece in order to machine the features in a single setup.

In our analysis of work holding, the only kind of work-holding device that we consider currently is vise-clamping. However, our method is extendable to account for other types of work-holding devices as well, and we intend to extend it to include work-holding methods such as toe clamps and machine clamps. We also want to include possibility of using other modular fixturing tools for identifying setups. As a longer-term goal, we would like to be able to identify the need for special fixturing, or the need for modification of part to add separate locating and supporting components to a part.

We develop a potential setup only after performing feasibility analysis for fixturing. Thus, instead of having to arbitrarily split a setup into more than one setup when we encounter a fixturability problem, we can systematically analyze different possible setup sequences. This allows us to determine the setup time more realistically than if only one setup sequence were considered.

In addition to estimating setup time, our methodology can be used to find out the whether a part is manufacturable using the available resources. Furthermore, it will be reasonably straightforward to extend it to identify attributes that prevent a proposed design from being manufacturable.

We intend to extend our approach to include an analysis of the overall manufacturing cost for a given part, rather than just setup time—and to provide suggestions on how to change the design in order to reduce the setup time. As such, it will become an important extension to our ongoing work on automatic generation of redesign suggestions [4].

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[4] Although it is difficult to compute an exact value for L, a good approximation can be computed reasonably quickly using binary search.

ACKNOWLEDGEMENTS

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