PED-Vol. 56, Quality Assurance Through Integration
of Manufacturing Processes and Systems
ASME 1992

GENERATION AND EVALUATION OF ALTERNATIVE OPERATION SEQUENCES

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ABSTRACT This paper presents a new and systematic approach to assist decision-making in selecting machining operation sequences. The approach is to produce alternative interpretations of design as different collections of machinable features, use these interpretations to generate alternative machining operation sequences, and evaluate the cost and achievable machining accuracy of each operations sequence. Given the operation sequences and their evaluations, it is then possible to calculate the performance measures of interest, and use these performance measures to select, from among the various alternatives, one or more of them that can best balance the need for a quality product against the need for efficient machining.

1 Introduction

Increasing global competition is challenging the U.S. manufacturing industry to bring competitively-priced, well-designed and well-manufactured products to market in a timely fashion. Since decisions made during the design stage can have significant effects on product cost, quality, and lead time, increasing research attention is being given to integrating engineering design and manufacturing, with a focus on design for manufacturability.

Consider the task of designing and manufacturing machined parts. A machined part is often considered as a collection of machinable features and thus the problem of evaluating the machinability of the part reduces to the problem of evaluating the machinability of the machinable features (Butterfield, et al., 1986, Shah, et al., 1988, Hummel, 1990, Shah, 1990). Note that, by the machinability of the part, we mean how easy it will be to achieve the required machining accuracy. This is somewhat broader than the usual usage of "machinability". One approach for evaluating the machinability of the machinable features is to compare each feature's machining tolerance and surface finish requirements against a list of process capabilities. This approach has been used for process selection in several generative process planning systems (Chang, et al., 1985, Nau, 1987, Brooks, et al., 1987, Ham, et al., 1988). However, this is not the most accurate way of determining machinability, for at least two reasons:

1. Whether or not a given machining process is capable of creating a given machinable feature will depend not only on the feature geometry, tolerance requirements, and surface finish requirements (Wu, 1977), but also on statistical variations in the process capabilities (Zhang, et al., 1991). In particular, random tool motion caused by tool wear or/and variations in basic material properties, such as hardness and ductility, in the material being machined is one of the major factors affecting the surface quality.

2. Existing approaches for obtaining machinable features from a CAD model will normally produce a single interpretation of the part as a collection of machinable features. However, there can be several different interpretations of the same part as different collections of machinable features—and each interpretation will lead to different sequences of machining operations for creating the same part (Vandenbrande, 1990). To determine the machinability of the part, all of the alternative interpretations should be generated and examined.

This paper discusses the development of a new approach whereby, given a proposed design for a machinable part, we can automatically generate the alternative machining operation, and then evaluate each of them to determine the achievable machining accuracies or costs. We anticipate that this information will be useful in several ways: (1) to provide feedback to the designer about possible problems that may arise in trying to meet the specified geometry and tolerances and (2) to provide information to the manufacturing engineer about alternative ways to machine the part, for use in process planning.

The paper is organized as follows. Section 2 describes our basic methodology for developing machining alternatives, and illustrates it on a specific case study. Section 3 discusses fundamentals of evaluating machinability, and illustrates it by continuing the case study begun in Section 2. Section 4 discusses our results, to illustrate how this information can be fed back to the designer to improve the product design. Section 5, the concluding section, discusses the significance and contribution of this work.

2 Generation of Alternative Operation Sequences

This section describes how we generate alternative operation sequences from the description of the object to be machined. Our approach is to generate alternative interpretations of the object as different collections of machinable features. No feature can be machined unless the cutting tool can reach it in order to machine it. In some cases, the cutting tool cannot reach a feature until some other features are machined first. Thus, each interpretation provides partial ordering constraints on the sequence in which the machining operations must be performed. We use these partial ordering constraints to generate one or more operation sequences from each interpretation. The details of this approach are shown in the procedure below:

Procedure for generating alternative operation sequences:

Step 1. Obtain the initial interpretation of the object as a set of machinable features.

Step 2. Generate all possible alternative interpretations of the object as other sets of machinable features, using feature manipulation operators.

Step 3. For each interpretation, generate operation sequences, discarding every operation sequence that violates common machining practice.

Step 4. For each operation sequence that has not been discarded, refine it to include rough and finishing operations.

In Step 2 of this procedure, alternate interpretations are generated by applying feature manipulation operators to all possible sets of adjacent features. These feature manipulation operators include extension (i.e., extending one feature into another adjacent features) and truncation (i.e., truncating the other feature by the same amount). A resulting interpretation is considered valid if all its member features conform to a pre-defined set of permissible machining features.

As a case study, consider the machined part shown in Fig. 1. It is a sleeve to fit in a slider bearing house. The two cylindrical holes H1 and H2 are designed for supporting the rotating shaft. Most of the time dimensional tolerance specification on H1 and H2 is tight. Moreover, the concentricity between the holes should be adequate to ensure the the reduced friction between sleeve and shaft during operations. The middle hole H3 (also called recess), functions as storage for lubrication. Therefore, the associated tolerance specifications are not very tight.

We now trace the operation of the procedure:

Step 1. One way to interpret the part as a collection of machinable features is interpretation (a)

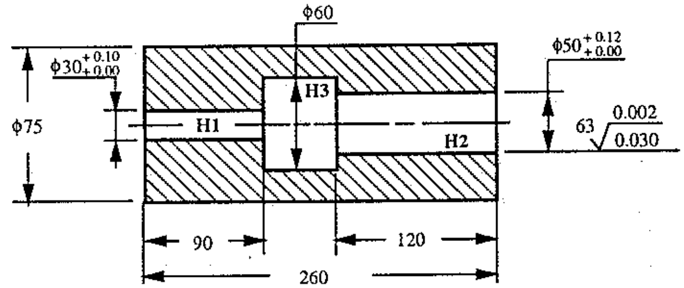


Figure 1 Design of the Part to be Machined

of Fig. 2: the holes h_{11} and h_{21}, and the recess h_{31}. Since the recess h_{31} is not accessible until the hole h_{21} has been machined, this interpetation has the partial ordering constraint that h_{31} must be machined after h_{21}.

Step 2. By applying feature manipulation operators to interpretation (a), it would be possible to produce interpretations (b), (c), and (d). Taking interpretation (b) as an example, h_{31} is not accessible until h_{23} has been machined, and h_{23} is not accessible until h_{12} has been machined. Thus, this intepretation has the partial ordering constraints that h_{31} must be machined after h_{22} and h_{22} must be machined after h_{12}.

Step 3. Each of the interpretations can be expanded into one or more operation sequences, depending upon the partial order constraints associated with the interpretations. Take interpretation (a) as an example, there are three possible operation sequences which satisfy its partial order constraint:

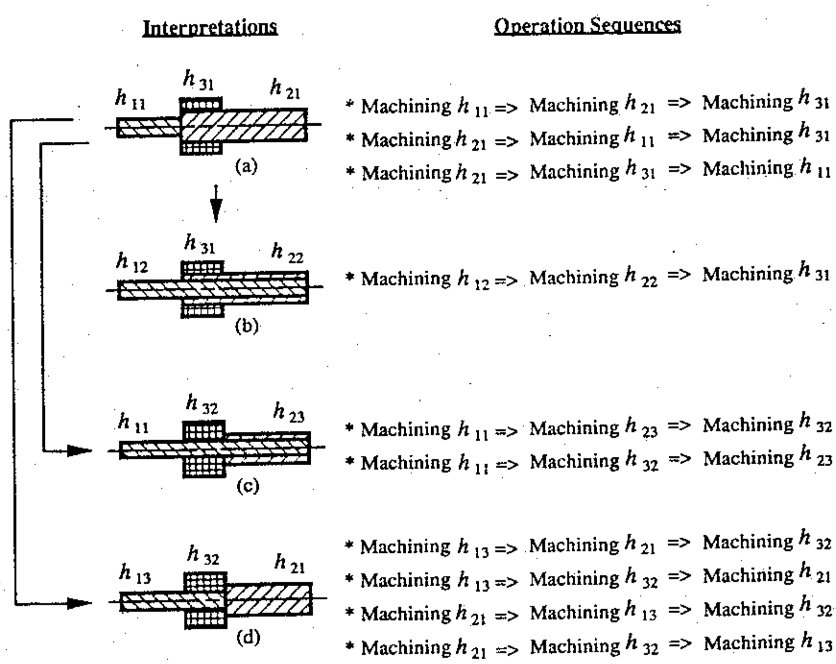


Figure 2 Alternative Intrepretations and Possible Operation Sequences

- machine $h_{11} \Rightarrow$ machine $h_{21} \Rightarrow$ machine h_{31};
- machine $h_{21} \Rightarrow$ machine $h_{11} \Rightarrow$ machine h_{31};
- machine $h_{21} \Rightarrow$ machine $h_{31} \Rightarrow$ machine h_{11}.

Because of accessibility constraints relating to the boring bar, it is preferable to machine the recess after both of the holes have been machined. Thus, we discard the third operation sequence above.

For a give interpretation, it is possible that there is only one operation sequence which satisfies the partial ordering constraint, or constraints. In interpretation (b), the operation sequence has to be:

- machine $h_{12} \Rightarrow$ machine $h_{22} \Rightarrow$ machine h_{31}.

Step 4. Now we refine these operation sequences to include the rough and finishing operations. This step results in possible candidate operation sequences. In interpretation (a), we may have two choices:

1. drill $h_{11} \Rightarrow$ bore $h_{11} \Rightarrow$ drill $h_{21} \Rightarrow$ bore $h_{31} \Rightarrow$ bore h_{21} (two setups).
2. drill $h_{21} \Rightarrow$ drill $h_{11} \Rightarrow$ bore $h_{31} \Rightarrow$ bore $h_{21} \Rightarrow$ bore h_{11} (one setup).

In interpretation (b), we may have a single choice:

1. drill $h_{12} \Rightarrow$ drill $h_{22} \Rightarrow$ bore $h_{31} \Rightarrow$ bore $h_{12} \Rightarrow$ bore h_{22} (one setup).

3 Machinability Evaluation

After producing the alternative interpretations of a given design and generating corresponding and possible operation sequences, focus of the decision making is the selection. Which one is preferable to use depends upon the particular optimization objectives. They could be the highest machining accuracy achievable, the lowest machining cost, or the minimized production time, or their combinations. In this section, we describe our methods for evaluate the achievable machining accuracy and the related costs in drilling and boring operations. We do this by illustrating how these methods work on two of the possible operation sequences identified in Section 2.

3.1 Case 1: Evaluate the highest machining accuracy achievable

In this paper, we select the operation sequence associated with interpretation (b) as an example to demonstrate the procedure for evaluating the highest machining accuracy achievable. The operation sequence is copied below:

1. drill $h_{12} \Rightarrow$ drill $h_{22} \Rightarrow$ bore $h_{31} \Rightarrow$ bore $h_{12} \Rightarrow$ bore h_{22} (one setup).

As shown in Fig. 2, h_{12}, h_{22}, and h_{31} will be made in one setup, offering an opportunity to achieve high machining accuracy. Thus, this operation sequence will be preferable when the specifications of the tolerances of the two holes and the concentricity between them are tight. Since all three of the features are rotational, the essential machining operations involved will be drilling and boring operations. It is a common practice to apply drilling operations for making holes and to apply boring operations to enlarge the drilled holes for tight tolerance and concentricity control.

3.1.1 Basic Mechanism Adopted for Drilling

To demonstrate the basic mechanism used to estimate achievable machining accuracy for drilling operations, below we present the steps in evaluating the achievable machining accuracy for drilling h_{12} and drilling h_{22}.

<u>Estimation of Incremental Increase in Hole Diameter</u> Drilling creates a hole whose diameter is larger than the diameter of the drilling tool. The difference between the hole's diameter and the drill's diameter is defined to be the *incremental increase* associated with the drilling process. Empirical data are often used to estimate the incremental increase associated with a specific drilling process. Table 1 lists some of the typical data used on the shop floor. As an example, the

incremental increase would be approximately 0.10 mm when a drill having 5 mm in diameter is used to make a hole on aluminum-based materials. Therefore, the diameter after drilling would be approximately 5.10 mm.

In the operation sequence listed above, if we use drill diameters of 29 mm and 49 mm to make h_{12} and h_{22}, respectively, then the corresponding incremental increases, as listed in Table 1, would be approximately 0.20 mm. Therefore, the diameters of h_{12} and h_{22} after drilling would be approximately 29.20 mm and 49.20 mm, respectively.

Table 1: Estimation of Incremental Increases during Drilling

Drill Diameter (mm)	Hardness of Workpiece Material (BHN)	Enlargement Coefficient
1.0 to 5.0	100	0.05 - 0.10
1.0 to 5.0	300	0.05 - 0.20
5.0 to 20	100	0.08 - 0.15
5.0 to 20	300	0.15 - 0.25
20 to 60	100	0.12 - 0.30
20 to 60	300	0.20 - 0.35

Estimation of Geometrical Variations In addition to the incremental increase in diameter, the holes produced by drilling have roundness, straightness, cylindricity, and other errors. Such errors are usually induced by the runout in attaching a drill to the machine tool, and the drill whirling motion due to the drill deflection during machining. As illustrated in Fig. 3a, these

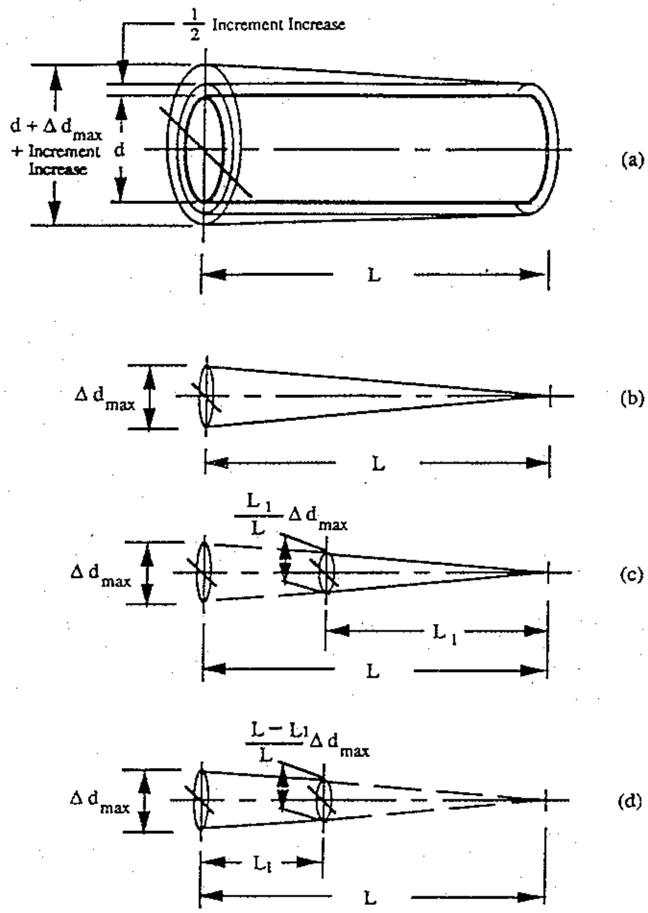


Figure 3 Analysis of Machining Errors during the Drilling Operation

machining errors vary along the axial direction. The error has its minimum value at one end of the hole where the drilling process starts, marked as Δd_{min} in Fig. 3b. It reaches its maximum value at other end of the hole, marked as Δd_{max} in Fig. 3b. The difference between Δd_{max} and Δd_{min} increases as the ratio of the length to diameter of a drill and the hardness of the workpiece material increase. In our work, we assume $\Delta d_{min} = 0$, and a database is constructed to determine Δd_{max} for a given drilling condition. Figure 4 outlines the basic structure of the database. Based on the constructed database, the values for Δd_{max} and Δd_{min} are 0.15 mm and 0.00 mm, respectively, in the current case study.

For ordinary holes, the above computation is sufficient to determine the maximum error value, Δd_{max}. However, h_{12} is not an ordinary hole, because part of it will later be removed when h_{22} is machined. Thus, as illustrated in Fig. 3c, the maximum error value Δd_{max} for h_{12} has to be modified, or reduced to $\frac{L_1}{L} \times \Delta d_{max}$. Note that the low limit of the achievable tolerance should be modified when the right portion is being removed, as illustrated in Fig. 3d. The modified low limit is given by $[\frac{L-L_1}{L}\Delta d_{max}]$. In both cases, L_1 represents the length of the remaining part of h_{12}. In the current case study, the low limit of the achievable tolerance of the remaining part of h_{12} would be 0.10 mm after the modification, instead of being equal to zero.

Consideration of Precision of the Machine Tool Being Used The achievable accuracy for a given machining operation is also related to the precision of the machine tool being used. If we have a high-precision machine tool (e.g., one with high spindle accuracy), we can significantly reduce machining errors such as Δd_{max} and Δd_{min}, as shown in Fig. 4. To account for machine tool precision, we multiply Δd_{max} and Δd_{min} by a modification factor, MF1. For example, consider a process plan in which all processes are to be performed in a single setup, on an engine lathe. Since the machine tool accuracy of lathes is better than the accuracy of drill presses, a value of 0.8 may be assigned to MF1.

Effects of Machining Parameters The achievable accuracy for a given machining operation is also related to machining parameters such as spindle speed and feed rate. For example, a high spindle speed increases the runout error, and drilling at a large feed rate leaves large feed marks on the drilled surface. To account for these effects, we multiply Δd_{max} and Δd_{min} by a second modification factor, MF2.

Determining the Achievable Tolerance Let the hole diameter be expressed as:

$$\text{Drill Size} \begin{array}{l} +\text{upper limit} \\ +\text{lower limit} \end{array} \tag{1}$$

Combining all of the above factors, we get the following formulas for the upper and lower limits of the achievable tolerances. Suppose the hole is drilled from right to left, as shown in Fig. 3. Then there are three cases.

For a complete hole, the tolerances are

$$\text{upper limit} = \text{Incremental Increase} + \Delta d_{max} \times \text{MF1} \times \text{MF2} \tag{2}$$
$$\text{lower Limit} = 0.0. \tag{3}$$

If the right side is later removed, then the tolerances are

$$\text{upper limit} = \text{incremental increase} + \Delta d_{max} \times \text{MF1} \times \text{MF2} \tag{4}$$
$$\text{lower limit} = \frac{L - L_1}{L}\Delta d_{max}. \tag{5}$$

If the left side is later removed, then the tolerances are

$$\text{upper limit} = \text{incremental increase} + [\frac{L_1}{L}\Delta d_{max}] \times \text{MF1} \times \text{MF2} \tag{6}$$
$$\text{lower Limit} = 0.0. \tag{7}$$

For our case study, Fig. 5 shows a graphical representation of the dynamic process to derive the achievable machining accuracy. For drilling h_{12}, it follows from Eqs. 4 and 5 that the upper and

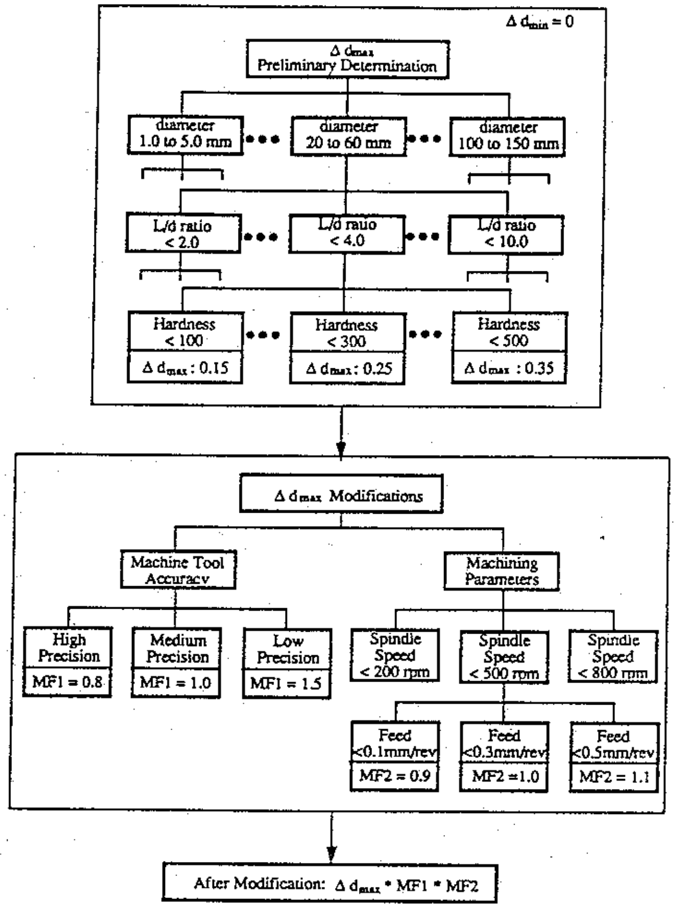


Figure 4 Hierarchical Structure for Δ d Determination

lower limits on the achievable tolerance for H1 are

$$\begin{aligned} \text{upper limit} &= \text{incremental increase} + \Delta d_{max} \times \text{MF1} \times \text{MF2} \\ &= 0.20 + 0.15 \times 0.8 \times 1.0 \\ &= 0.32 \quad (\text{mm}) \end{aligned}$$

and

$$\begin{aligned} \text{lower limit} &= \frac{L - L_1}{L} \Delta d_{max} \\ &= \frac{260 - 90}{260} \times 0.15 \\ &= 0.10 \quad (\text{mm}) \end{aligned}$$

It should be pointed out that the achievable tolerance for H1 is

$$\text{upper limit} - \text{lower limit} = 0.32\text{mm} - 0.10\text{mm} = 0.22\text{mm}.$$

Had we done this computation using Eqs. 2 and 3, we would have gotten a much looser value, 0.32. The difference indicates the importance of relaxing the machining requirement in the first operation of the selected operation sequence. In the first operation, a tight tolerance control would be an over-constraint which would result in an unnecessary cost increase.

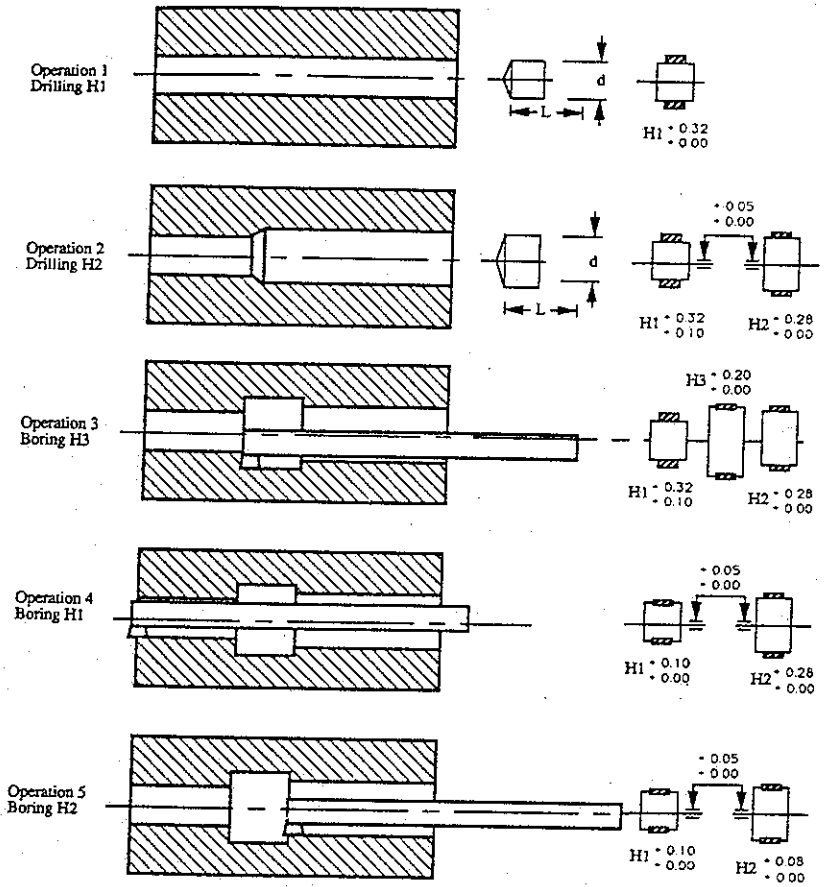


Figure 5 Alternative Way 1: Achieving a possibly high Machining Accuracy

In the second operation (drilling h_{22}), it follows from Eqs. 2 and 3 that the achievable tolerance is [0.28, 0.00]. This achievable tolerance is tighter than that in the first operation, due the higher rigidity of the drill.

Estimation of the Concentricity Error Figure 5 also indicates the dynamic generation of concentricity error at the end of the second operation. Note the symbol to represent the achievable concentricity between H1 and H2 after drilling H2. It means that that the two holes of H1 and H2 may not be aligned along a unified axis due to the machining errors resulted in the first and second operations of the selected operation sequence. In practice, possible errors in the concentricity mainly come from the errors in the machine tool movement, the drill runouts, and the fixturing error when the workpiece is being machined on different setups or orientations. We use the following formula to calculate the concentricity error between two machined holes.

$$\begin{aligned} \text{concentricity error} &= \frac{\frac{1}{2}(\Delta d_{max} + \Delta d_{min})_{H1} + \frac{1}{2}(\Delta d_{max} + \Delta d_{min})_{H2}}{2} \times \text{MF1} \times \text{MF2} \\ &\quad + \text{errors due to multiple setups} \\ &= \frac{\frac{1}{2} \times 0.15 + \frac{1}{2} \times 0.10}{2} \times 0.8 \times 1.0 + 0.0 = 0.05 \text{ mm} \end{aligned} \tag{8}$$

In the current case study, the concentricity error is calculated from the first term in Eq. 8. The second term is considered to be zero since the workpiece remains at an identical position during the two drilling operations.

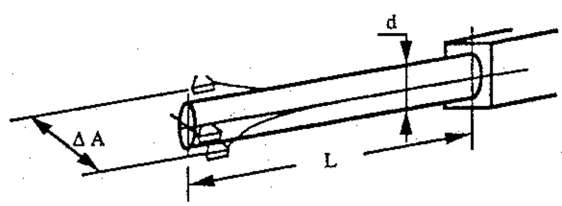
3.1.2 Achievable Tolerance for Boring

In order to illustrate our approach for estimating achievable accuracy during boring, we now describe the steps in evaluating the achievable machining accuracy for boring H3, H1, and H2.

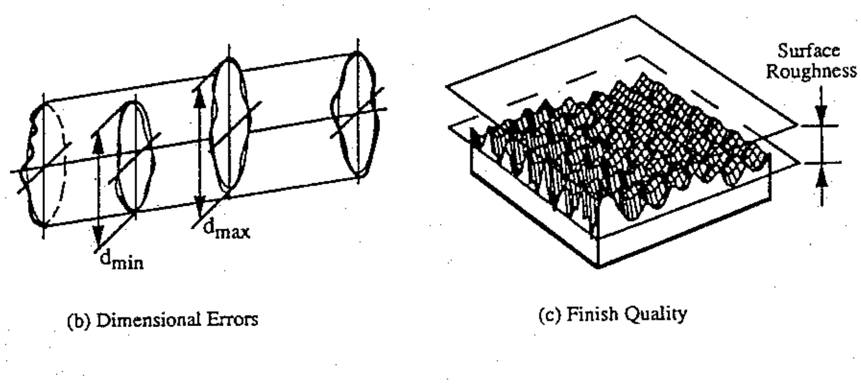
Estimation of the Number of Machining Passes Boring operations are widely used on the shop floor as finishing or semi-finishing operations to enlarge an existing hole. However, the inherent properties of the long, slender boring bar make it susceptible to severe vibration during machining. To maintain a stable and satisfactory operation, the material removal rate during machining has to be limited. This may require more than a single pass to complete the machining operation.

In general, a single pass during the machining operation is sufficient if specifications on dimensional accuracy and finish quality are low. The enlargement of H3 from the existing H1 is a typical example, since the surface quality of a recess is of little relevance to its function of storing lubricant. For surfaces where dimensional accuracy and finish quality are major concerns, two passes during the machining operation are usually needed. The first pass removes the major surface irregularities resulting from drilling, and the second pass produces a smooth surface and assures the dimensional accuracy. To achieve higher machining accuracy, grinding, reaming, or other finish machining operations are often recommended. In our work, we assume that, depending on the required specification, either a single-pass operation or a two-pass operation is needed during boring. During a two-pass operation, the first pass removes 2/3 of the excessive material, and the second pass removes the remaining 1/3.

Estimation of Achievable Machining Accuracy for Each Pass Figure 6 illustrates the error generation due to the boring bar vibration during machining. The vibration magnitude, ΔA, has its direct influence on dimensional accuracy, such as d_{max} and d_{min}) shown in Fig. 6b, and finish quality. Major factors contributing to the error generation can be the hardness of the workpiece



(a) Vibration of Boring Bar Causes Machining Errors



(b) Dimensional Errors

(c) Finish Quality

Figure 6 Analysis of Machining Errors during the Boring Operation material, the total machining load, the slenderness ratio of the boring bar, the slenderness ratio of the workpiece, and the progress of tool wear during machining. Similar to the method used to determine the achievable tolerance during drilling, we calculate the achievable tolerance during boring based on the following formulas:

Let the hole diameter be expressed as:

$$\text{Boring Dia}\ {}^{+\text{upper limit}}_{+\text{lower limit}} \tag{9}$$

For the first pass:

$$\text{upper limit} = \text{incremental increase} + \Delta B \times \text{MF1} \times \text{MF2} \times \text{MF3} \tag{10}$$

$$\text{lower limit} = \text{incremental increase.} \tag{11}$$

For the second pass:

$$\text{upper limit} = \text{incremental increase} + [\Delta B \times \text{MF1} \times \text{MF2} \times \text{MF3}] \times 0.5 \tag{12}$$

$$\text{lower limit} = \text{incremental increase.} \tag{13}$$

In Eqs. 10 and 12, ΔB represents a nominal value of the machining error. Figure 7 presents the basic structure of a database prepared for selecting the value ΔB under various machining

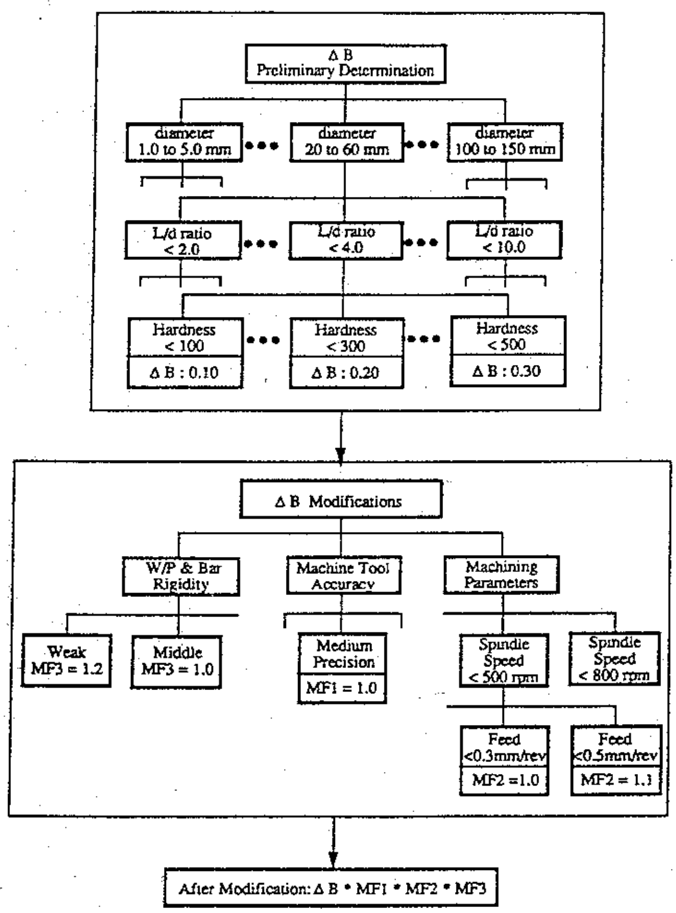


Figure 7 Hierarchical Structure for Δ B Determination

conditions. In Eqs. 10 and 12, the MF's are modification factors to account for the machine tool accuracy, rigidity of the workpiece-boring bar combination, and machining parameters. The lower limit of the achievable tolerance is determined by the incremental increase necessary for completing a single pass during machining. In our work, the numerical value of the lower limit is set to equal the achievable tolerance of its preceding operation. In Eq. 12 a proportionality coefficient of 0.5 is used in evaluating the upper limit of the achievable tolerance for the second pass. This indicates that the tolerance achievable during a finish cut is higher than the tolerance achievable during a rough or semi-finish cut. Figure 5 illustrates the transition of the achievable tolerance from a drilling operation to a boring operation. The tolerance range narrows as the boring operation progresses.

__Estimation of the Concentricity Error__ As a semi-finishing or finishing operation, the boring process significantly reduces the concentricity error resulting from the drilling operation. It is evident that the achievable concentricity tolerance between the two enlarged holes is also related to the achievable machining accuracy for each of them. In our work, the following formula is used to calculate the concentricity error between the two machined holes after the boring operation. For the first pass:

$$\begin{aligned}\text{concentricity error} &= \frac{1}{2}(\Delta B_{H1} + \Delta B_{H2}) \times \text{MF1} \times \text{MF2} \\ &\quad + \text{errors due multiple setups}\end{aligned} \tag{14}$$

For the second pass:

$$\begin{aligned}\text{concentricity error} &= [\frac{1}{2}(\Delta B_{H1} + \Delta B_{H2}) \times \text{MF1} \times \text{MF2} \times \text{MF3}] \times 0.5 \\ &\quad + \text{errors due to multiple setups}\end{aligned} \tag{15}$$

Figure 5 also illustrates the transition of the concentricity error from a high value to a low value during the boring operation.

3.2 Case 2: Evaluate the Minimum Production Cost Achievable

When the concentricity tolerance between H1 and H2 is not tight, the main objective in process planning may be to achieve the cost reduction while maintaining an acceptable machining accuracy. Under such circumstances, the operation sequence of having two setups associated with interpretation (a) may be used to machine the part.

drill h_{11} ⇒ bore h_{11} ⇒ drill h_{21} ⇒ bore h_{31} ⇒ bore h_{21} (two setups).

It is evident that the two setups indicate hole h_{11} is made from side 1 and hole h_{21} is made from side 2. Figure 8 illustrates the five necessary machining operations and their sequence.

The procedure discussed in Section 3.1 for evaluating achievable tolerances can be used for the evaluation of the achievable tolerance for each of these five operations. In this case, we present a procedure to evaluate the production cost associated with these machining operations.

The total cost of a machining operation consists of the two components, the fixed and the variable cost. Both of these costs serve as a basis for the economics of machining operation planning. The fixed cost mainly consists of depreciation of machining equipment, maintenance disbursements, and administrative expenses. The variable cost consists of the costs which vary in accordance with the level of production activity. Typical examples of variable cost would be the cost related to the machining activities, tooling, and auxiliary activities. Note that the fixed cost is the part of the total cost which remains at a constant level even when different operation sequences are used. In this case study, we focus our attention to the effect of different operation sequences on the variable cost or the production cost while the fixed cost is assumed to be constant.

__Cost Related to the Machining Activity__ These costs include the total labor, utility, and the operation overhead cost. The following equation presents a quantitative evaluation of this cost.

$$\text{machining cost} = (\text{wage rate} + \text{overhead}) \times \text{machining time} \tag{16}$$

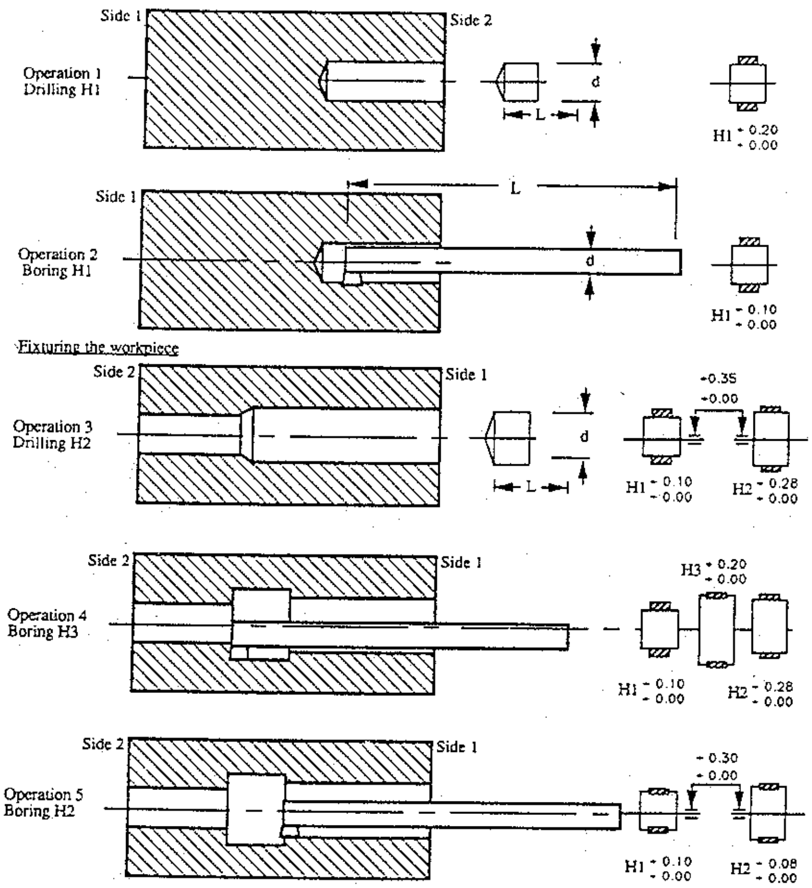


Figure 8 Alternative Way 2: Achieving a Low Machining Accuracy with a Low Cost

Where the machining time evaluation is based on a specific machining operation. For the drilling operation, it is given by

$$\text{machining time} = \frac{\text{travel distance}}{\text{spindle speed} \times \text{feed}} \quad (\text{min}) \tag{17}$$

For the boring operation, it is given by

$$\text{machining time} = \frac{\pi(D_f + D_i)}{2} \frac{\text{travel distance}}{\text{feed}} \frac{1}{\text{Cutting Speed}} \times (\text{number of passes}) \tag{18}$$

Where D_f and D_i are the diameters in mm before and after machining. The cutting speed is calculated from $\pi \times D \times$ spindle speed. The units of feed and cutting speed are mm/rev and mm/min, respectively.

Cost Related to Tooling Due to tool wear during machining, tool replacement is required when the useful tool life is over. The tooling cost consists of two terms. One is a fraction of the cost of the tool while the other is the cost of the tool replacement process. The following equation presents these two costs in quantitative form.

$$\text{tooling cost} = \frac{\text{machining time}}{\text{tool life}}[\text{tool cost} + (\text{tool changing time})(\text{wage rate} + \text{overhead})] \tag{19}$$

Machining Operation	Spindle Speed (rpm)
Drilling H1	200
Boring H1	400
Drilling H2	120
Boring H3	200
Boring H2	240

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Table 2 Cost Analysis of the Machining Operations

Machining Operation	Spindle Speed (rpm)	Feed (mm/rev)	Machining Time (min)	Auxiliary Time (min)	Machining Cost ($)	Tooling Cost ($)	Auxiliary Cost ($)	Total Cost ($)	Fixed Cost ($)	Production Cost ($)
Drilling H1	200	0.2	2.25	3	0.90	0.93	1.20	3.03	1.00	4.03
Boring H1	400	0.1	4.50	3	2.70	1.29	1.80	5.79	2.00	7.79
Drilling H2	120	0.2	6.25	3	2.50	3.63	1.20	7.33	1.00	8.33
Boring H3	200	0.1	1.25	3	0.75	0.36	1.80	2.91	2.00	4.91
Boring H2	240	0.1	6.00	3	3.60	1.72	1.80	7.12	2.00	9.12

Total Cost: $34.18

Where the tool life can be evaluated from the tool life-cutting speed relationship. Following equation presents this relationship in quantitative form.

$$\text{tool life} = \left(\frac{\text{referenced cutting speed}}{\text{selected cutting speed}}\right)^{1/n} \times \text{referenced tool life} \qquad (20)$$

Where n is the tool life exponent. Value of n mainly depends on the tool and the part materials. For example, n ranges from 0.20 to 0.30 for carbide tool materials when machining carbon steel materials. Equation 20 depicts the inverse relationship between the tool life and the cutting speed. This implies that the time needed for tool replacement could offset the time saved due to the reduced machining time from high speed machining.

Cost Related to Auxiliary Activities This part of the variable cost includes costs of loading and unloading the part being machined, and returning the tool to its initial position. This can be evaluated by

$$\text{auxiliary cost} = (\text{wage rate} + \text{oberhead})(\text{auxiliary time}) \qquad (21)$$

Determination of the Production Cost Total cost which combines these three cost components presents a comprehensive picture of the economics aspects in process planning. In this case study, the total variable cost is evaluated by summing up the three cost components. Under the assumption that the fixed cost is at a constant level and independent of the operation sequence, the production cost is given by

$$\begin{aligned} \text{Production Cost} &= \text{Variable Cost} + \text{Fixed Cost} \\ &= \text{machining cost} + \text{tooling cost} + \text{auxiliary cost} + \text{Fixed Cost} \qquad (22) \end{aligned}$$

Table 2 presents the data from the cost analysis. Each row lists the estimated cost components for individual machining operation. By summing up the five individual production costs, the total production cost associated with this process plan is $34.18 as indicated in Table 2. By examining the production cost associated with the operation of drilling H1, it is listed as $4.03. Note that, in the previous case study, the travel distance of drilling H1 would be 260 mm, instead of 90 mm in the current study. Consequently, a higher production cost can be expected in the previous case study. Therefore, the economic merit of the operation sequence used in this evaluation over other operation sequences is quite evident.

4 Discussion of Results

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time. This has led to the evolution of the philosophy of concurrent engineering, which involves identifying design elements that pose problems for manufacturing and quality control, and changing the design, if possible, to overcome these problems during the design stage. This integration is believed to produce *robust designs* (Taguchi, et al., 1989, Dehnad, 1989). Although this approach appears quite attractive, its large scale practical implementation has eluded the design and manufacturing engineers.

One of the missing links in achieving *robust designs* is the virtual absence of theoretical groundwork for the generation of manufacturing alternatives. In absence of such work, most attempts to implement robust design consider a single manufacturing plan (supposedly the best one), and recommend design changes based on this plan. But in general, there may be several alternative ways to manufacture a given design. In order to determine whether the design is robust, all of these alternatives should be generated and examined, to determine how well each one balances the need for a quality product against the need for efficient machining.

In this paper, we have described a way to generate a variety of alternative process sequences based on alternate feature interpretations, and then evaluate each process sequence to determine the best one to select. The primary steps in this analysis can be summarized as follows:

1. First, we generate alternate interpretations of the part as different collections of machinable features.

2. Second, for each collections of machinable features, we generate one or more process sequences capable of producing those features.

3. Third, we evaluate each process sequence, in order to predict the achievable machining accuracy for each of the planned machining operations, and estimate the achievable production cost at its minimum level.

To make these ideas clear to the reader, we have demonstrated how to do this analysis on a very simple example. However, the same approach can be used for analyzing much more complex parts.

The information produced by this analysis can be used in several ways:

For designers. When a designer proposes a design of a machinable part, it will allow him/her to see the alternative ways in which it might be machined, to obtain information what tolerances are achievable, and to predict if the achievable tolerances will become better or worse as the feature dimensions are changed. Our approach provides the designer with information on the relevant production cost, and allows him/her to balance the needs for efficient manufacturing of a quality product. Such an ability to study and evaluate a proposed design aids the goals of concurrent engineering, by pushing the manufacturing concerns upstream into the design stage. Therefore, we believe that our approach will provide a powerful tool for engineering designers.

For process planners. Heuristic approaches and operations-research optimization techniques can be used to select optimal process plans based on defined objectives (such as cost or machining accuracy). However, their lack of credibility and requirements of excessive data have limited their applications on the shop floor. Our approach is intended to address this problem. The algorithm for generating alternative operation sequences for a given part design provides a powerful consultation tool for the production engineer to use during process planning. It offers information about what processes and process parameters are most desirable over the various ways in which the part might be machined. In addition, results from the evaluations of the achievable tolerances for individual machining operations can be organized into the production documentation, such as a typical route sheet. In fact, Figs. 5 and 8 can be viewed as a preliminary version of the route sheet to indicate operation sequence, associated machine tools, and machining accuracy control.

5 Conclusion

We have described a new approach for use in the concurrent engineering of products and manufacturing processes. Its uniqueness lies in the generation and evaluation of machining alternatives. For a given part design, the approach generates a variety of alternative process sequences based on feature interpretations, and then evaluates these sequences to determine their cost and machining accuracy. The work presented in this paper clearly demonstrates the benefits and importance of an early integration of the manufacturing knowledge and design specifications in the product development cycle. The integration offers an effective information flow between the product designer and process planner. It will give the production engineer knowledge about what processes and process parameters are most desirable over the various ways in which the part might be machined; and will give the product designer a better understanding of about the robustness of the design, and how the design might be changed to improve its manufacturability.

Acknowledgement

This work was supported in part by NSF Grant NSFD CDR-88003012 to the University of Maryland Systems Research Center, NSF grant IRI-8907890 to the University of Maryland Computer Science Department, and the University General Research Board.

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