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Generation of Machining Alternatives for Machinability Evaluation*

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Abstract

This paper presents a new methodology for evaluating the machinability of a machined part during the design stage of the product development cycle, so that problems related to machining can be recognized and corrected while the product is being designed. Our basic approach is to perform a systematic evaluation of machining alternatives throughout each step in the design stage. This involves three basic steps: (1) generate alternative interpretations of the design as different collections of machinable features, (2) generate the various possible sequences of machining operations capable of producing each interpretation, and (3) evaluate each operation sequence, to determine the relevant information on achievable quality and associated costs. The information provided by this analysis can be used not only to give feedback to the designer about problems that might arise with the machining, but also to provide information to the manufacturing engineer about alternative ways in which the part might be machined.

1 Introduction

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time. Such considerations have led to the evolution of the philosophy of *design for manufacture*, which involves identification of design elements that pose problems for manufacturing and quality control, and changing the design if possible to overcome these problems during the design stage.

In general, there may be several alternative ways to manufacture a given design. 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 describe how to address this task, in the domain of rotational machined parts. For machining purposes, the part is often considered as a collection of machinable features [4, 12], but there can be several different interpretations of the part as several different collections of machinable features. Different features require different machining steps, so different feature interpretations will yield different plans for machining the part. To evaluate how well each machining step can do at creating the corresponding feature, we must take into account the feature geometry, tolerance requirements, surface finish requirements, and statistical variations in the process capabilities.

We use the following generate-and-test approach:

1. Generate alternative interpretations of the design as different collections of machinable features.
2. For each interpretation, generate the various possible sequences of machining operations capable of producing that interpretation.
3. Evaluate each operation sequence, to determine whether it is capable of meeting the desired tolerance and surfaces requirements, and if so, what the associated machining costs and times will be.

This approach will produce a large number of alternative operation sequences, and then eliminate most of them based on machining considerations.

2 Definitions

A *solid* is a regular, semi-analytic set [11]. If R is any solid, then $b(R)$ is the *boundary* of R and $i(R)$ is the *interior* of R. Note that $R = i(R) \cup b(R)$ and that $i(R) \cap b(R) = \emptyset$. A *patch* of R is a regular, semi-analytic subset of the boundary $b(R)$.

A *machined part* (or just a *part*) is the finished component P to be produced by a set of machining operations on a piece of *stock* S. We will represent both the part and the stock as solids. The *delta volume* (i.e., the volume to

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be machined), is the solid $\Delta = S - P$. For example, in Fig. 1, the shaded portion of the figure is the part, and the unshaded portion is the delta volume.

A *machining feature* is the volume removed from the stock by a single machining operation. We will represent each machining feature as a solid, together with the following properties of the surfaces bounding the solid:

Accessibility. Let F be a feature, and p be a patch of F. If p separates air from metal, say that p is *blocked*. If p separates air from air, then we say that p is *unblocked.*

Relation to the part and the stock. A *part patch* is a patch of V that is also a portion of the part's boundary; i.e., if p is a part patch then $p \subseteq b(V)$ and $p \subseteq b(P)$. A *stock patch* is a patch of V that is also a portion of the stock's boundary; i.e., if p is a stock patch then $p \subseteq b(V)$ and $p \subseteq b(S)$. A *construction patch* is is a patch of V that is not a portion of either the part's boundary or stock's boundary; i.e., if p is a construction patch, then $p \subseteq b(V)$ and $i(p) \cap b(P) = i(p) \cap b(S) = \emptyset$.

Note that every part patch is blocked, and every stock patch is unblocked. Whether a construction patch is blocked or unblocked depends on the order in which the features are made.

In several other papers, we consider prismatic parts [5, 10, 2, 6, 7]—but in this paper, we are only considering rotational parts, so we will only consider rotational machining features. These can be defined mathematically using a cylindrical coordinate system (r, θ, z). Let f be any semi-analytic function, and let r_0, r_1, z_0, z_1 be any nonnegative numbers such that $0 < r_0 < r_1$ and $z_0 < z_1$. Then a rotational machining feature may be any of the following solids:

1. An *inner radial feature* is the set of all points (r, θ, z) such that $z_0 \leq z \leq z_1$ and $r_0 \leq r \leq f(z)$. This solid has four faces: a cylindrical face $r = r_0$, which must be unblocked; two planar faces $z = z_0$ and $z = z_1$, which need not necessarily be blocked or unblocked; and a face $r = f(z)$, which must be at least partially blocked. Fig. 2 gives some examples of inner radial features.
2. An *outer radial feature* is the set of all points (r, θ, z) such that $z_0 \leq z \leq z_1$ and $f(z) \leq r \leq r_0$. This solid has four faces: a cylindrical face $r = r_0$, which must be unblocked; two planar faces $z = z_0$ and $z = z_1$, which need not necessarily be blocked or unblocked; and a face $r = f(z)$, which must be at least partially blocked. Fig. 3 gives some examples of outer radial features.
3. An *axial feature* is the set of all points (r, θ, z) such that $r_0 \leq r \leq r_1$ and $z_0 \leq z \leq f(r)$. This solid has four faces: a planar face $z = z_0$, which must be unblocked; two cylindrical faces $r = r_0$ and $r = r_1$, which must be at least partially blocked; and a face $z = f(r)$, which must be at least partially blocked. Fig. 4 gives an example of an axial feature.
4. A *hole* is the set of all points (r, θ, z) such that $0 \leq r \leq r_1$ and $z_0 \leq z \leq f(r)$. This solid has three faces: a planar face $z = z_0$, which must be unblocked;

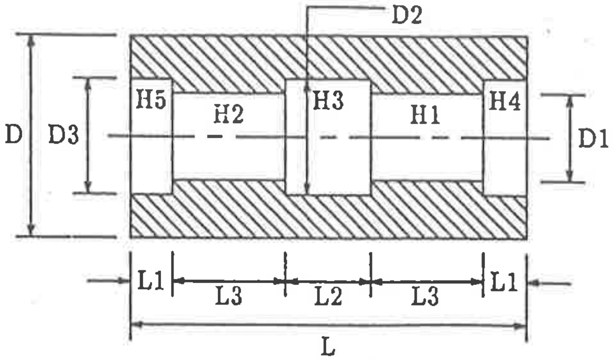

Figure 1: Part P_1, a sleeve to fit in a slider bearing house.

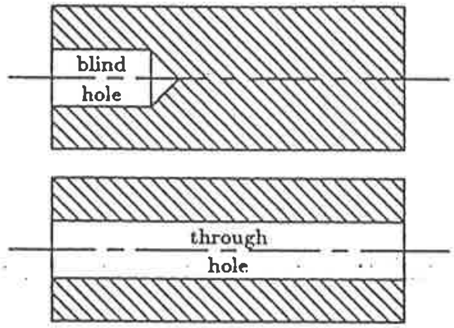

Figure 2: Examples of inner radial features.

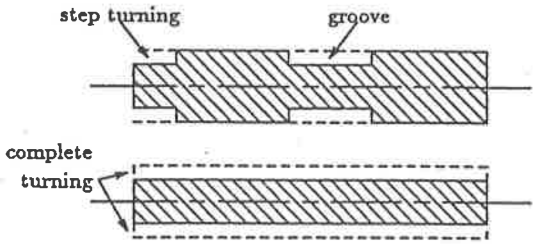

Figure 3: Examples of outer radial features.

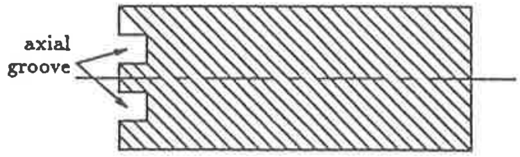

Figure 4: Example of an axial feature.

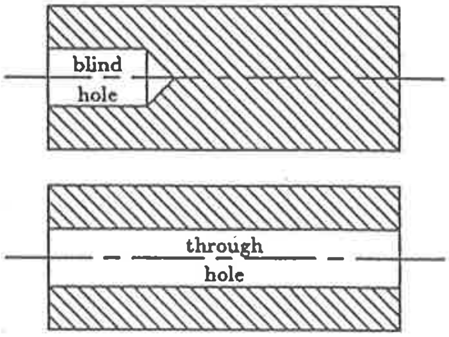

Figure 5: Examples of holes.

a cylindrical face $r = r_1$, which must be at least partially blocked; and a face $z = f(r)$, which need not necessarily be blocked or unblocked. Fig. 5 gives some examples of holes.

Let P be any part and S be any stock. Then a *feature-based model* (or FBM) for P and S is any set of features M having the properties that (1) for any two features $F_1, F_2 \in M$, $F_1 \cap F_2 = \emptyset$, and (2) the union of all the features in M is the delta volume $\Delta = S - P$. Intuitively, an FBM is an interpretation of the delta volume as a set of machining features. For example, Fig. 6 shows several FBM's for the part P_1. All of these FBM's are *equivalent*; i.e., they represent the same part and stock.

Let M be an FBM, and F_1 and F_2 be any two features in M. Then $i(f_1) \cap i(f_2) = \emptyset$. F_1 and F_2 are *adjacent* if $b(F_1) \cap b(F_2) \neq \emptyset$. If F_1 and F_2 are adjacent, then it follows that the patch $p = b(F_1) \cap b(F_2)$ is a construction patch.

Let F_1 and F_2 be any two adjacent features in an FBM M, and suppose there is a feature F such that:

1. F_1 is a proper subset of F;
2. $F_2 - F$ is a feature or collection of features;
3. there is no feature G such that $F \subset G$ and $F_2 - G$ is a feature or collection of features.

Then we say that F is an *extension* of F_1 into F_2. It follows that there is at most one extension of F_1 into F_2, and that if F is this extension, then the set of features M' produced by removing F_1 and F_2 from M and replacing them with F and $F_2 - F$ is an equivalent FBM. We say that M' is a *reinterpretation* of M.

3 Generating Alternative Feature Interpretations

In [5], we described a way to produce alternative interpretations of the same object as different collections of features as the result of algebraic operations on the features, and a system for generating alternative interpretations by performing these algebraic operations. Although our mathematical framework was quite general, the utility of the approach was limited, primarily because the definitions of the features and the operators did not take into account many of the essential properties of common machining operations. As described below, we are developing a methodology that overcomes these limitations.

First, we need to get an initial feature interpretation from the CAD model. There are three primary approaches for this task. In *human-supervised feature recognition*, a human user examines an existing CAD model to determine what the manufacturing features are [1]. In *automatic feature recognition*, the same feature recognition task is performed by a computer system [13]. In *design by features*, the designer specifies the initial CAD model in terms of features [12].

By starting with a single FBM M for P and S, and performing successive reinterpretations, it is possible to produce the set $\mathcal{M}$ of all FBM's for P and S. Let G be the digraph whose node set is $\mathcal{M}$ and whose edge set is

$$E = \{(M, M') | M' \text{ is a reinterpretation of } M\}.$$

We call this digraph the *interpretation space* for P and S. As an example, Fig. 6 shows the interpretation space for the part P_1 shown in Fig. 1.

4 Generating Operation Sequences

This section describes our approach for generating alternative operation sequences for each feature interpretation of a part.

Due to accessibility [9] and setup constraints [3], the set of features that comprise an object cannot necessarily be machined in any arbitrary sequence. Instead, these constraints will require that some features be machined before or after other features. However, for a given set of features, usually there will be more than one order in which the features can be machined.

As an example, consider Interpretation 4 of Fig. 6. In this interpretation, h_{34}, h_{44}, and h_{54} must all be made after the hole h_{14}. However, once we have made h_{14}, we can make h_{34}, h_{44}, and h_{54} in any order. Thus, there are six possible orderings for h_{34}, h_{44}, and h_{54}, so Interpretation 4 corresponds to six possible orders in which to make the features.

Let M be an FBM and F be a feature in M, and suppose F has no stock faces. Then F cannot be machined unless it has at least one construction face. For each construction face f of F, there are two possibilities:

Case 1: f is also a subface of some other feature F'. Then F will be accessible once F' has been created, so it will be possible to machine F any time after F' has been machined.

Case 2: f can be partitioned into subfaces f_1 and f_2 that are subfaces of some other features F_1' and F_2', respectively. (The only way this can happen is if F_1' and F_2' were created by splitting a through hole, as described in Section 3.) This means that f will be accessible once F_1' and F_2' have been created, so it will be possible to machine F any time after both F_1' and F_2' have been machined.

The *time-order graph* for M is the hypergraph (M, A), where A is the set containing all hyperarcs $(\{F'\}, F)$ such that F and F' satisfy Case 1 above, and all hyperarcs $(\{F_1', F_2'\}, F)$ such that F, F_1', and F_2' satisfy Case 2 above. For example, Fig. 6 gives the time-order graph for each interpretation.

The time-order graph for M represents all possible time orderings in which the features might be machined. Graph-traversal techniques can be used to generate all possible time orderings consistent with the time-order graph. For example, consider the time-order graph for Interpretation 4 of Fig. 6. There are six time orderings consistent with this graph:

make h_{14}, make h_{34}, make h_{54}, make h_{44}; (TO1)
make h_{14}, make h_{34}, make h_{44}, make h_{54}; (TO2)
make h_{14}, make h_{54}, make h_{34}, make h_{44}; (TO3)
make h_{14}, make h_{54}, make h_{44}, make h_{34}; (TO4)
make h_{14}, make h_{44}, make h_{34}, make h_{54}; (TO5)
make h_{14}, make h_{44}, make h_{54}, make h_{34}. (TO6)

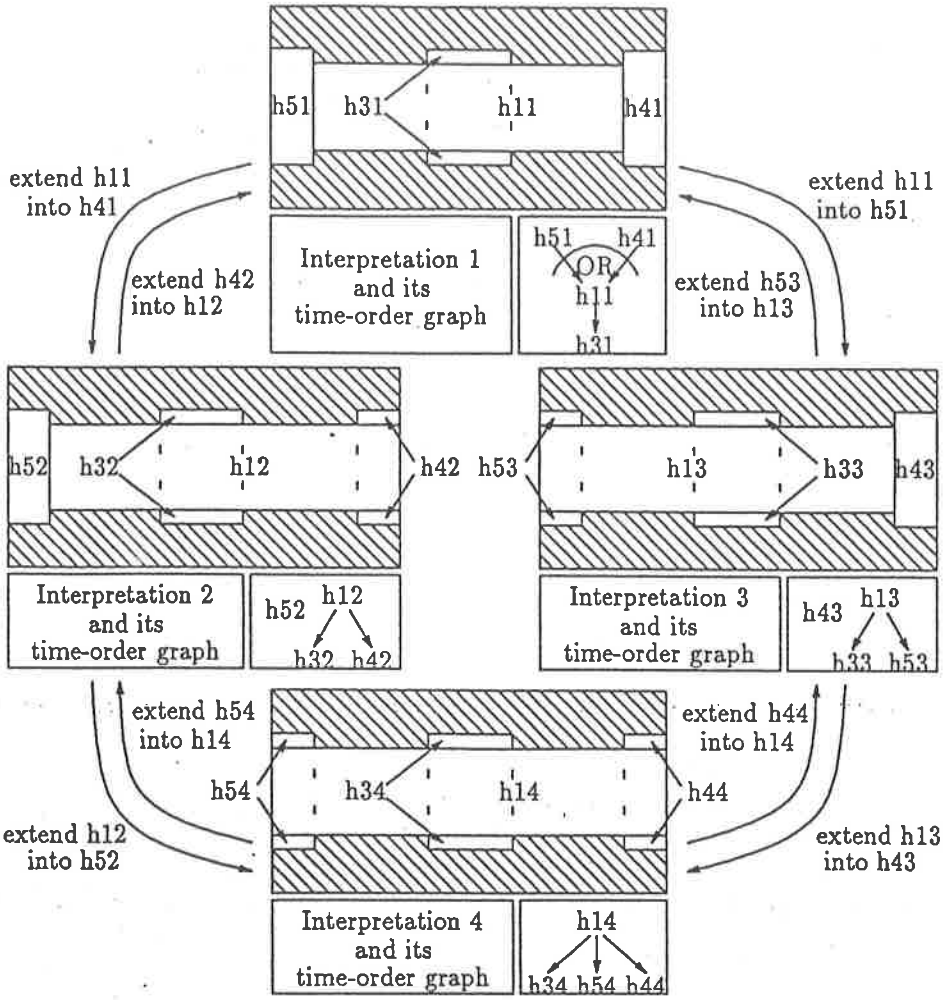

Figure 6: Alternative interpretations of P_1, and their time-order graphs.

If each feature could be made using a single machining operation, then FIND-TIME-ORDERINGS(M, A) would provide us with all possible orderings for these operations. However, in order to create a feature, sometimes we will need several machining operations: a *roughing* operation followed by one or more *finishing* operations. In this case, the time-order graph only gives us the precedence constraints for the roughing operations. For example, here is one possible sequence of roughing operations corresponding to TO1 above:

$$\text{drill } h_{14}, \text{ drill } h_{34}, \text{ bore } h_{54}, \text{ bore } h_{44}. \qquad \text{(OS1)}$$

For the finishing operations, the constraints given in the time-order graph do not apply; the constraints on the finishing instead involve the nature of the machining operations themselves, such as how the part will be fixtured (i.e., held in place) during each operation, how many setups (i.e., changes of fixturing) will be needed, etc.). A discussion of these issues is beyond the scope of this paper—but as an example, here is one way to augment OS1 to include finishing operations as well:

$$\text{drill } h_{14}, \text{ drill } h_{44}, \text{ bore } h_{44}, \text{ bore } h_{14}, \text{ bore } h_{34}, \text{ bore } h_{54}. \qquad \text{(OS2)}$$

This operation sequence is illustrated in Fig. 7.

5 Machinability Evaluation

Because of the need for quality assurance on the shop floor, extensive work has been done on evaluating machinability for a given design.[1] Much of the data relevant for machining operation planning is available in machining data handbooks such as [8]. Also, mechanistic models have been developed to provide quantitative mappings from machining parameters (such as cutting speed, feed, and depth of cut) to the performance measures of interest (such as surface finish and dimensional accuracy) [16, 14]. Research on machining economics has produced quantitative models for evaluating costs related to machining operations [15, 14]. Optimization techniques have been applied to these quantitative models to seek machining parameters that minimize the variable cost, or maximize the production rate and profit rate associated with machining operations.

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[1] By the machinability of a part, we mean how easy it will be to achieve the required machining accuracy. This is somewhat broader than the usual usage of "machinability."

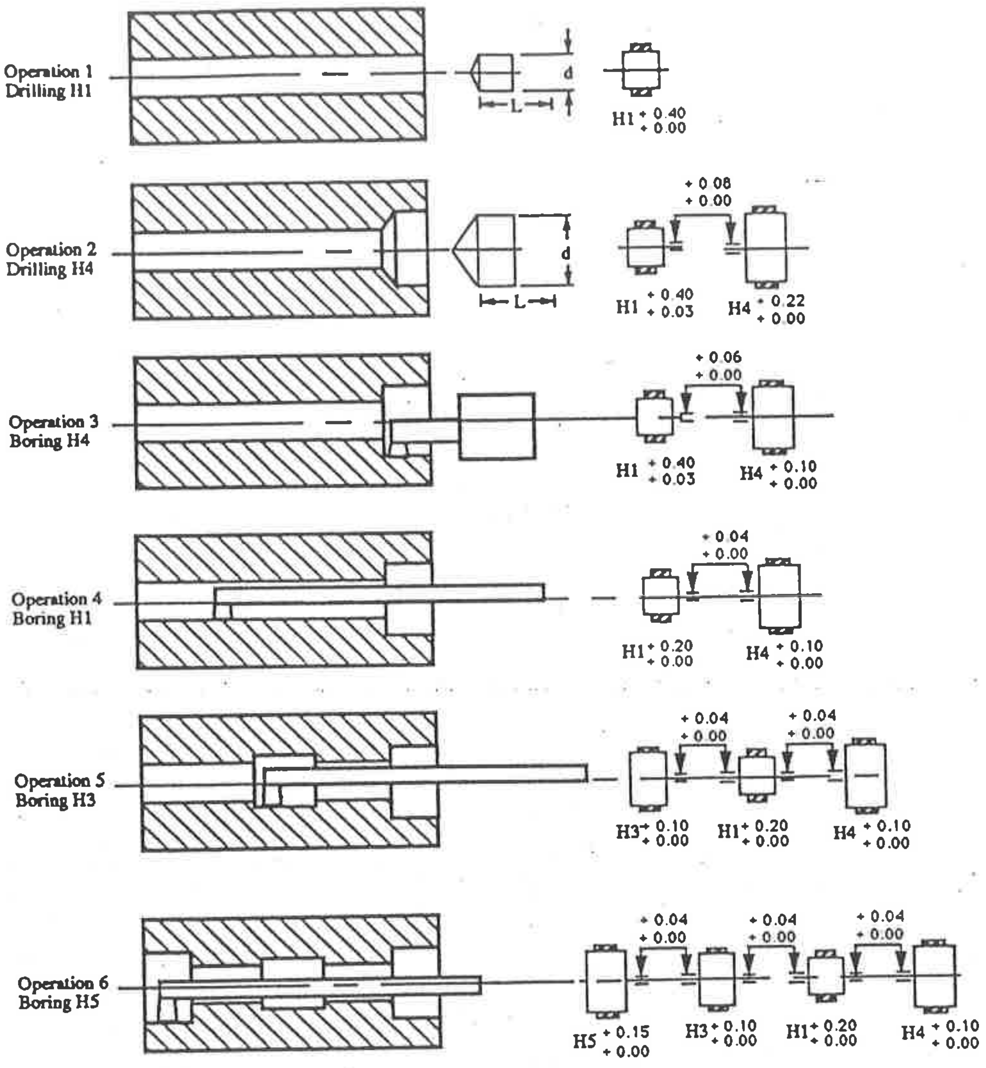

Figure 7: Operation sequence OS2.

Below, we discuss how to estimate the costs incurred by the machining operations, and the tolerances produced by these operations.

5.1 Estimating Achievable Tolerance

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give tolerance specifications on the nominal geometry, to specify how large these variations are allowed to be.

Given a candidate operation sequence, the machining data for that sequence, the feature's dimensions, and the material from which the part is to be made, we want to evaluate whether or not it can satisfactorily achieve the tolerance specifications. The capabilities of the machining process depend on the following factors:

1. The machining system parameters, such as the feed rate, cutting speed, depth of cut, and structural dynamics. Their effects on the process capabilities can be modeled and evaluated deterministically [8, 9].
2. The natural and external variations in the machining process. For example, variations in hardness in the material being machined cause random vibration, which is one of the major factors affecting the surface quality. Such variations are unavoidable in practice, and are best dealt with statistically. This introduces a margin of error into our calculations of the process capabilities. The margin of error needs to be large enough that product quality is maintained, and yet small enough that the cost of the machining process is manageable [16, 17, 9].

Some of the more important formulas from [17, 9] are reproduced in Appendix A.

For example, suppose that the part shown in Fig. 1 has the following dimensions: $D_1 = 40$, $D_2 = 60$, $D_3 = 60$, $L_1 = 30$, $L_2 = 40$, and $L_3 = 80$. For drilling h_{14} (the first operation in OS2), it follows from Eqs. 2 and 3 that the

Table 1: Cost analysis for operation sequence OS2

machining operation	spindle speed (rpm)	feed (mm/rev)	machining time (min)	aux. time (min)	machining cost	tooling cost	aux. cost	fixed cost	total cost
drill h_{14}	250	0.30	5.20	3	\$2.60	\$3.47	\$1.50	\$1.00	\$8.57
drill h_{44}	200	0.15	1.00	3	0.50	1.40	1.50	1.00	4.40
bore h_{44}	400	0.10	0.75	3	0.60	1.29	2.40	2.00	6.29
bore h_{14}	400	0.10	9.75	3	7.80	4.12	2.40	2.00	16.32
bore h_{34}	400	0.10	1.00	3	0.80	1.72	2.40	2.00	6.92
bore h_{54}	400	0.10	0.75	3	0.60	1.29	2.40	2.00	6.29
								Total Cost:	\$48.79

upper and lower limits on the achievable tolerance for H1 are

$$\begin{aligned}\text{upper limit} &= I + \Delta d_{\max} \times \text{MF1} \times \text{MF2} \\ &= 0.20 + 0.25 \times 0.8 \times 1.0 \\ &= 0.40 \quad \text{(mm)};\end{aligned}$$

$$\begin{aligned}\text{lower limit} &= (L - L_1)\Delta d_{\max}/L \\ &= (260 - 230)0.25/260 \\ &= 0.03 \quad \text{(mm)};\end{aligned}$$

where I is the *incremental increase*, i.e., the difference between the hole's diameter and the drill's diameter. The achievable tolerance for H1 is

$$\begin{aligned}\text{upper limit} - \text{lower limit} &= 0.40\text{mm} - 0.03\text{mm} \\ &= 0.37\text{mm}.\end{aligned}$$

In OS2's second operation (drilling h_{44}), it follows from Eqs. 2 and 3 (in Appendix A) that the achievable tolerance is $[0.22, 0.00]$. This achievable tolerance is tighter than that in the first operation, due the higher rigidity of the drill.

The concentricity error is calculated from the first term in Eq. 4, resulting in a concentricity error value of 0.08. The second term of the equation is considered to be zero since the workpiece (i.e., the partially machined part) remains at an identical position during the two drilling operations.

The machining tolerances for the other steps of OS2 can be calculated similarly; the results appear in Fig. 7.

5.2 Estimating the Costs

The total cost of a machining operation consists of two components, the fixed cost 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.

Extensive research has been done on estimating the costs for the machining operations; we discuss the details in [15, 9]. Some of the more important formulas from [15, 9] are reproduced in Appendix B.

As an example, Table 1 presents the cost data for operation sequence OS2, calculated using the cost-estimation formulas in Appendix B. Each row lists the estimated cost components for an individual machining operation; the final column of each row sums these cost components to obtain the machining operation's production cost. The total production cost, \$48.79, is the sum of the production costs of the six machining operations.

5.3 Evaluating Tradeoffs

In OS2, h_{14} through h_{54} will be made in one setup as shown in Fig. 3, offering an opportunity to achieve high machining accuracy. Thus, OS2 will be preferable when there are tight tolerance specifications (particularly the concentricity tolerance between H4 and H5). 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.

Generation and evaluation of alternatives produces not only OS2, but also other operation sequences that are both less accurate and less costly. If the tolerance specifications are not tight, then the main objective in process planning may be to achieve a low cost while maintaining an acceptable machining accuracy. In this case, some of these other less costly operation sequences may be acceptable.

By generating and evaluating the alternatives, we can determine which of them best satisfy the machining tolerances and cost objectives.

6 Conclusions

We have presented a new approach for evaluating machinability of a machined part during design stage of the product development cycle, so that problems related to manufacturing can be recognized and corrected while the product is being designed. Our basic approach is to perform a systematic evaluation of machining alternatives throughout each step in the design stage. Such an analysis can be useful in two ways:

1. to provide feedback to the designer about the machinability of the design, so the designer can modify the design if necessary to balance the need for efficient machining against the need for a quality product;

2. to provide information to the manufacturing engineer about alternative ways in which the part might be machined, for use in developing process planning alternatives depending on machine tool availability.

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A Estimating Achievable Tolerances

A.1 Drilling

Suppose a hole is drilled from right to left as shown in Fig. 8, and let the hole diameter be expressed as:

$$\text{Drill Size}\ {}^{+\text{upper limit}}_{+\text{lower limit}} \tag{1}$$

For a complete hole, the dimensional tolerances are

$$\text{upper limit} = \begin{cases} I + \Delta d_{\max} \times \mathrm{MF1} \times \mathrm{MF2} \\ \quad \text{for a complete hole} \\ I + \Delta d_{\max} \times \mathrm{MF1} \times \mathrm{MF2} \\ \quad \text{if right side later removed} \\ I + [\frac{L_1}{L} \Delta d_{\max}] \times \mathrm{MF1} \times \mathrm{MF2} \\ \quad \text{if left side later removed} \end{cases} \tag{2}$$

$$\text{lower limit} = \begin{cases} 0.0 \quad \text{for a complete hole} \\ \frac{L-L_1}{L} \Delta d_{\max} \\ \quad \text{if right side later removed} \\ 0.0 \quad \text{if left side later removed} \end{cases} \tag{3}$$

In the above equations, I is the *incremental increase*, i.e., the difference between the hole's diameter and the drill's diameter. Table 2 lists some of the typical values used for I on the shop floor. $\Delta d_{\max}$ is the maximum error caused by deflection during the drilling process. MF1 is a modification factor to account for machine tool precision. MF2 is a modification factor to account for 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). L is the length of the complete hole, and L_1 is the length of the portion of the hole that remains if part of it is later removed.

Fig. 9 shows a decision tree for determining $\Delta d_{\max}$, MF1, and MF2. For example, if the operation is to be performed on a lathe, a value of 0.8 will be used for MF1, since a lathe is considered to be a high-precision machine tool (compared to, say, a drill press).

Table 2: Incremental Increases during Drilling

Drill Diameter (mm)	Hardness of Workpiece Material (BHN)	Incremental Increase
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

We use the following formula to calculate the concentricity error between two drilled holes H_1 and H_2:

$$\begin{aligned}&\text{concentricity error}\\&\quad= \frac{(\Delta d_{\max}+\Delta d_{\min})_{H1}+(\Delta d_{\max}+\Delta d_{\min})_{H4}}{4}\\&\qquad\times \mathrm{MF1}\times\mathrm{MF2}\\&\qquad+\text{errors due to multiple setups}\end{aligned}\tag{4}$$

In the above equation, $\Delta d_{\max}$, MF1, and MF2 are as before, and $\Delta d_{\min}$ is the minimum error caused by deflection during the drilling process.

A.2 Boring

We calculate the dimensional tolerance that can be achieved by boring using the following formulas:

Let the hole diameter be expressed as:

$$\text{Boring Dia}\ {}^{+\text{upper limit}}_{+\text{lower limit}}\tag{5}$$

For the first pass:

$$\text{upper limit} = \Delta B\times\mathrm{MF1}\times\mathrm{MF2}\times\mathrm{MF3}\tag{6}$$

$$\text{lower limit} = 0.0\tag{7}$$

For the second pass:

$$\text{upper limit} = \frac{\Delta B\times\mathrm{MF1}\times\mathrm{MF2}\times\mathrm{MF3}}{2}\tag{8}$$

$$\text{lower limit} = 0.0\tag{9}$$

In Eqs. 6 and 8, ΔB represents a nominal value of the machining error, and the MF's are modification factors to account for the machine tool accuracy, rigidity of the workpiece-boring bar combination, and machining parameters. In Eq. 8, the proportionality coefficient of 0.5 is used to indicate that the tolerance achievable during a finish cut is higher than the tolerance achievable during a rough or semi-finish cut.

To determine ΔB, MF1, MF2, and MF3 under various machining conditions, we have a decision tree for boring that is similar to the one for drilling in Fig. 9.

As a semi-finishing or finishing operation, the boring process significantly reduces the concentricity error resulting from the drilling operation. We use the following formulas to calculate the concentricity error between two bored holes H_1 and H_2. For the first pass:

$$\begin{aligned}&\text{concentricity error}\\&\quad=\frac{1}{2}(\Delta B_{H1}+\Delta B_{H2})\times\mathrm{MF1}\times\mathrm{MF2}\\&\qquad+\text{errors due multiple setups}\end{aligned}\tag{10}$$

For the second pass:

$$\begin{aligned}&\text{concentricity error}\\&\quad=\frac{1}{4}(\Delta B_{H1}+\Delta B_{H2})\times\mathrm{MF1}\times\mathrm{MF2}\times\mathrm{MF3}\\&\qquad+\text{errors due to multiple setups}\end{aligned}\tag{11}$$

In the above equations, ΔB_{H1} and ΔB_{H2} are the values of ΔB for the holes H1 and H2, respectively.

B Cost Estimation Formulas

$$\begin{aligned}&\text{machining cost}\\&\quad=(\text{wage rate}+\text{overhead})\text{machining time}\end{aligned}\tag{12}$$

For drilling operations,

$$\begin{aligned}&\text{machining time}\\&\quad=\frac{\text{travel distance}}{\text{spindle speed}\times\text{feed}}\quad(\text{min})\end{aligned}\tag{13}$$

For boring operations,

$$\begin{aligned}&\text{machining time}\\&\quad=\frac{\pi(D_f+D_i)}{2}\times\frac{\text{travel distance}}{\text{feed}}\\&\qquad\times\frac{\text{number of passes}}{\text{cutting speed}}\end{aligned}\tag{14}$$

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.

$$\begin{aligned}&\text{tooling cost}\\&\quad=\frac{\text{machining time}}{\text{tool life}}[\text{tool cost}+\\&\qquad(\text{tool change time})(\text{wage rate}+\text{overhead})]\end{aligned}\tag{15}$$

$$\begin{aligned}&\text{tool life}\\&\quad=\left(\frac{\text{referenced cutting speed}}{\text{selected cutting speed}}\right)^{1/n}\\&\qquad\times\text{referenced tool life}\end{aligned}\tag{16}$$

where n is the tool life exponent.

$$\begin{aligned}&\text{production cost}\\&\quad=\text{machining cost}+\text{tooling cost}\\&\qquad+\text{auxiliary cost}+\text{fixed cost}\end{aligned}\tag{17}$$

where the fixed cost is assumed to be constant, and

$$\begin{aligned}&\text{auxiliary cost}\\&\quad=(\text{wage rate}+\text{overhead})(\text{auxiliary time})\end{aligned}\tag{18}$$

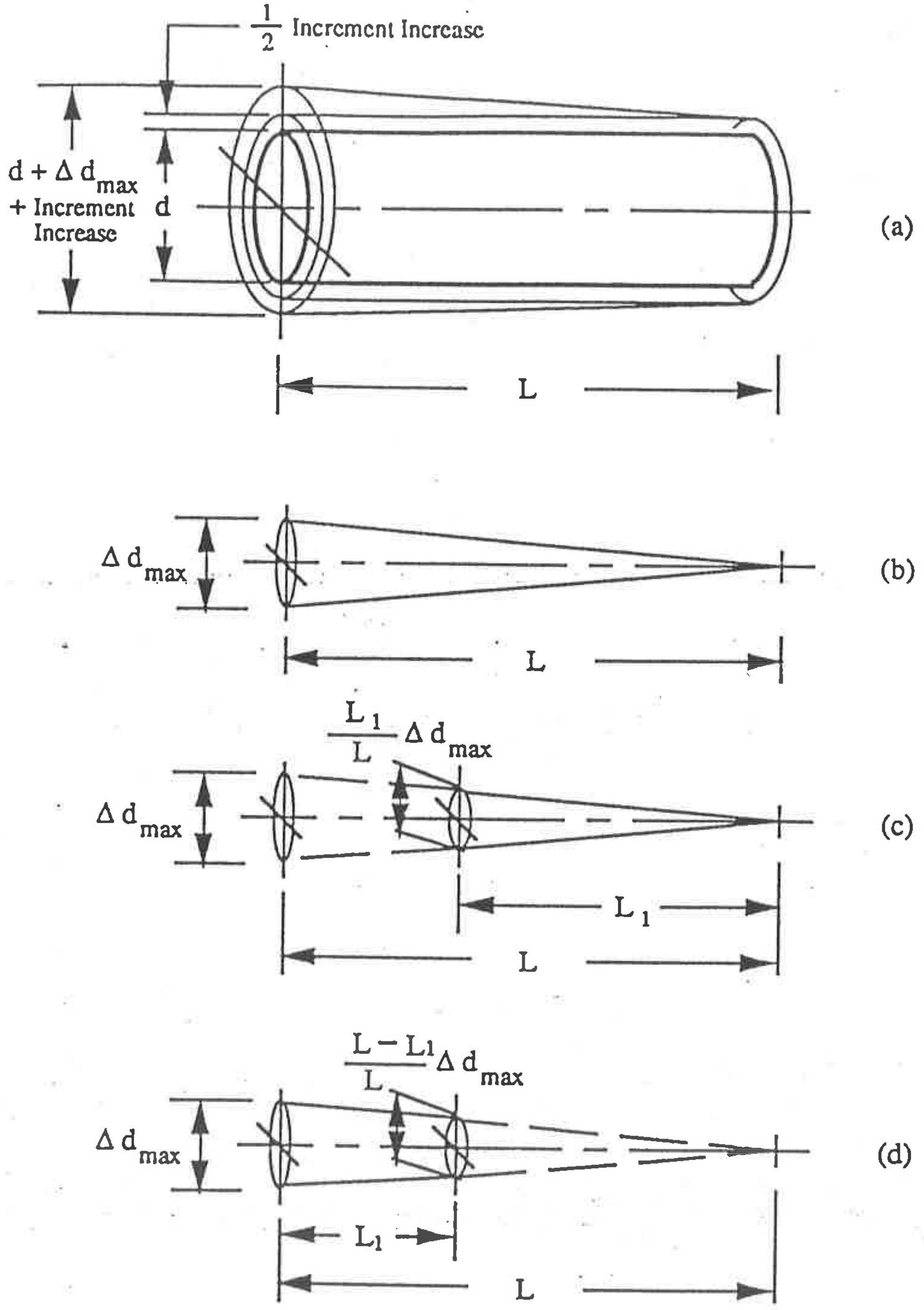

Figure 8: Analysis of machining errors during drilling operations.

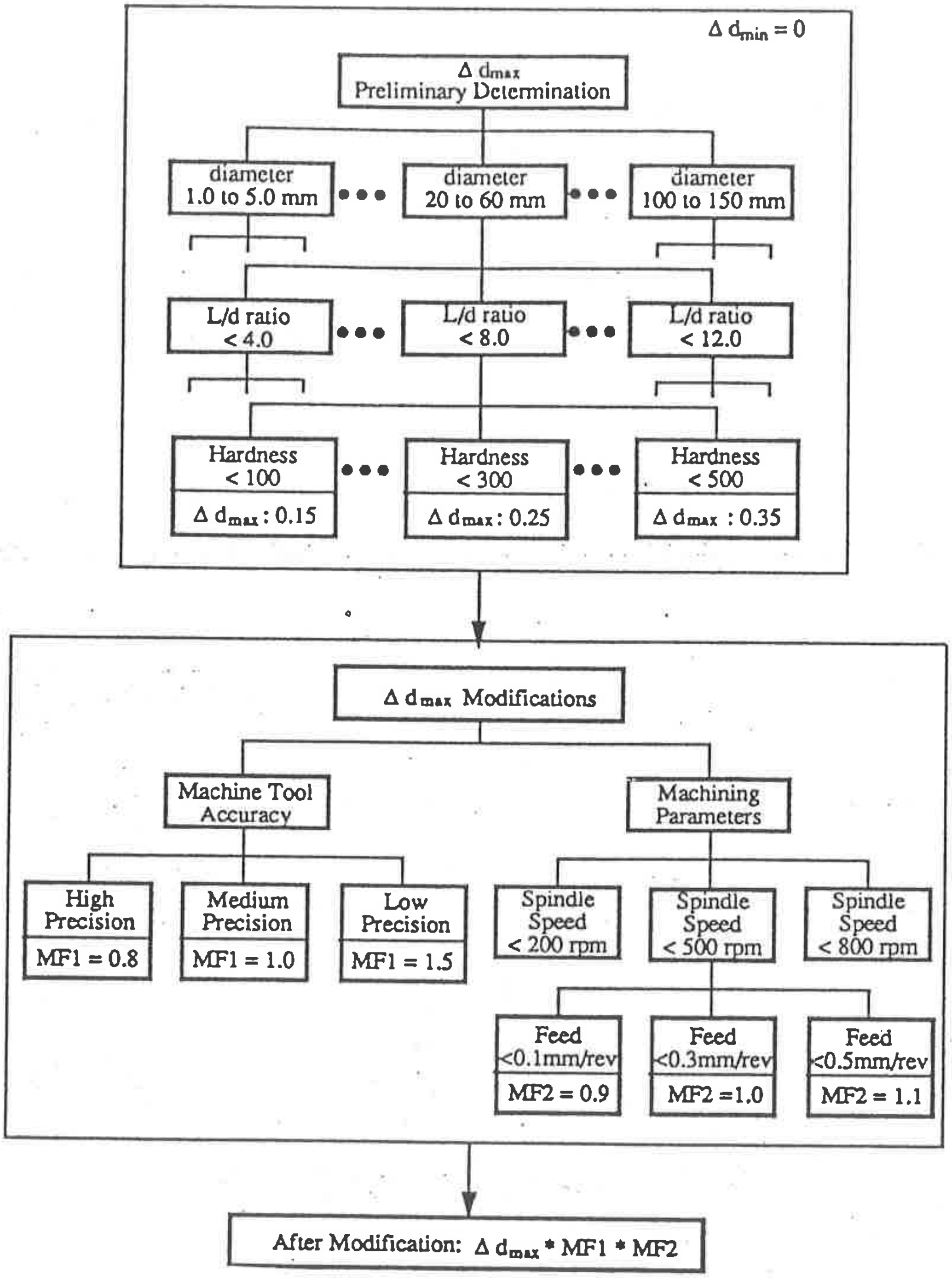

Figure 9: Decision tree for drilling.