This special section presents six reports on concurrent engineering.

Concurrent Evaluation of Machinability During Product Design

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Decisions made during the design of a product can significantly affect its cost, quality, and lead time. We are developing a methodology for evaluating the machinability of a part during the design stage so that problems related to machining can be recognized and corrected while the product is being designed.

There may be several alternative ways to machine a given design. Our approach is to systematically generate and evaluate these alternatives and thus determine how well they balance the need for a quality product against the need for efficient machining. There are three basic steps:

(1) Generate alternative interpretations of the design as different collections of machinable features.

(2) Generate various possible sequences of machining operations capable of producing each interpretation.

(3) Evaluate each operation sequence to get information about achievable quality and associated costs.

The results of this analysis will provide feedback to the designer about problems that might arise with the machining, and information to the manufacturing engineer about which machining processes and process parameters are most desirable.

Generating machining alternatives. A machined part P is the result of performing a set of machining operations on a piece of stock S. A *machining feature* is the volume removed by a single machining operation. A *feature-based model* is a collection of disjoint features whose union is $S - P$. Two FBMs are equivalent if they represent the same part. Given an FBM, we can generate other equivalent FBMs using feature reinterpretation operators to map sets of features into other sets of features. These are similar (but not identical) to the operators described by Karinthi and Nau.[1]

For example, consider the rotational part P_1 whose cross section is shown in Figure 1 (for details, see Nau, Zhang, and Gupta[2]). This is a sleeve to fit in a slider-bearing house. The two holes H1 and H2 are designed for supporting the rotating shaft, and the recess H3 provides storage for lubrication. Feature reinterpretation operators produce several FBMs for P_1 (see Figure 2).

Accessibility and setup constraints will require that some features be machined before or after others. To represent these constraints, we use a hypergraph called a *time-order graph*. Several operation sequences will generally satisfy the time-order graph. For example, here is an op-

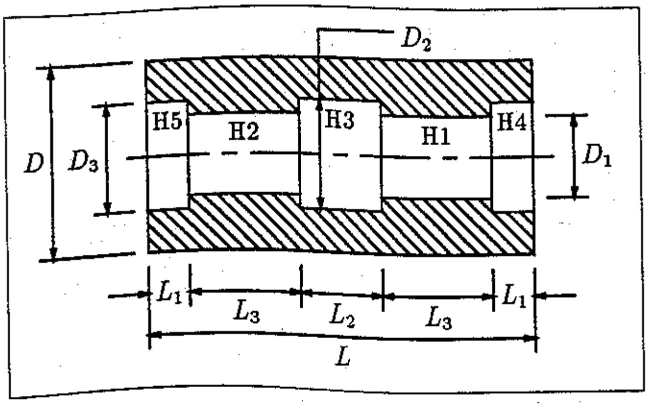

Figure 1. Cross section of part P_1, a sleeve to fit in a slider-bearing house.

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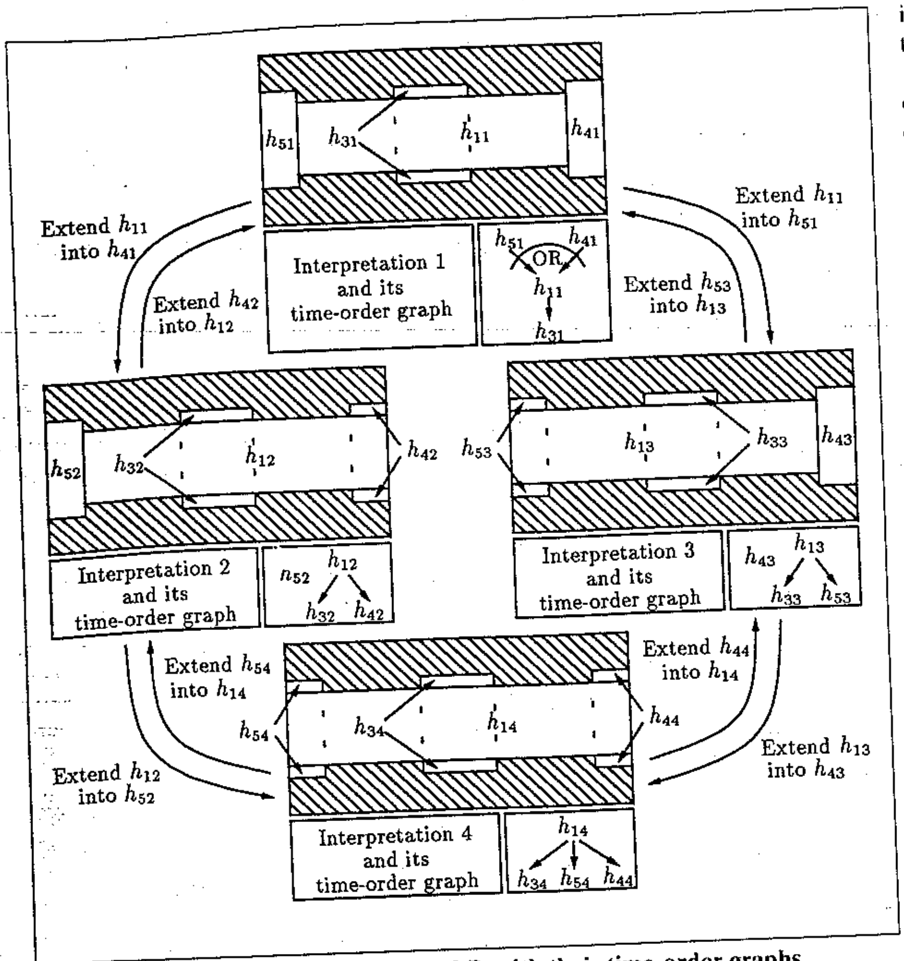

Figure 2. Alternative interpretations of P_1 with their time-order graphs.

eration sequence that satisfies the time-order graph for interpretation 4 in Figure 2:

drill h_{14}, drill h_{44}, bore h_{34}, bore h_{54} (OS1)

Operation sequence 1 contains only one machining operation for each feature, but creating a feature will sometimes require a *roughing* operation followed by one or more *finishing* operations. The time-order graph gives the precedence constraints only for the roughing operations. The constraints on the finishing operations involve the nature of those operations: how the part will be *fixtured* (held in place) during each operation, how many *setups* (changes of fixturing) will be needed, etc. Here is one way to augment OS1 to include finishing operations:

drill h_{14}, drill h_{44}, bore h_{44}, bore h_{14}, bore h_{34}, bore h_{54} (OS2)

Machinability evaluation. The capabilities of a machining process depend on the machining-system parameters (for example, the feed rate, cutting speed, depth of cut, and structural dynamics), whose effects can be modeled deterministically. They depend also on the natural and external variations in the machining process (for example, vibration caused by variations in the hardness of the workpiece material), which are best dealt with statistically. On the basis of these considerations, we have developed a deterministic/statistical simulation model for evaluating whether or not a candidate operation sequence can satisfactorily achieve the specified machining tolerances, given its machining data, the feature's dimensions, and the material to be machined.[2,3]

We have also developed formulas for estimating an operation sequence's production cost.[2,3] These formulas include fixed costs (depreciation of equipment, maintenance disbursements, administrative expenses, etc.) and costs that vary according to the level of production activity (costs related to machining activities, tooling, auxiliary activities, etc.).

For example, suppose the dimensions of the part P_1 are $D_1 = 40$, $D_2 = 60$, $D_3 = 60$, $L_1 = 30$, $L_2 = 40$, and $L_3 = 80$. On the basis of our techniques for machinability evaluation, Figure 3 graphically represents operation sequence 2 and the machining tolerances produced by each of its steps. As the cost computation in Table 1 shows, the estimated total production cost for OS2 is \$48.79.

Evaluating trade-offs. In OS2, h_{14} through h_{54} will be made in one setup, as shown in Figure 3, offering an opportunity to achieve high machining accuracy. However, OS2 is not the only operation sequence for creating the part P_1. OS2 will be preferable when there are tight tolerance specifications (particularly the concentricity tolerance between H4 and H5); but if the tolerance specifications are not tight, then some of the other (less accurate) operation sequences may produce acceptable tolerances at lower cost. By generating and evaluating the alternatives, we can determine which best satisfy the machining tolerances and cost objectives.

Conclusions. Our new approach for evaluating the machinability of a part during the design stage is to perform a systematic generation and evaluation of machining alternatives. The results of such an analysis can be useful in two ways: to provide feedback to the designer about the machinability of the design so that problems related to manufacturing can be recognized and corrected while the product is being designed, and to provide information to the manufacturing engineer for use in developing process planning alternatives, depending on machine tool availability. For further details, see Nau, Zhang, and Gupta.[2] ■

Table 1. Cost analysis for operation sequence 2.

Machining Operation	Spindle Speed (rpm)	Feed (mm/rev)	Machining Time (min)	Aux. Time (min)	Machining Cost	Tooling Cost	Aux. Cost	Fixed Cost	Total Operation 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 sequence cost:		$48.79

Acknowledgments

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

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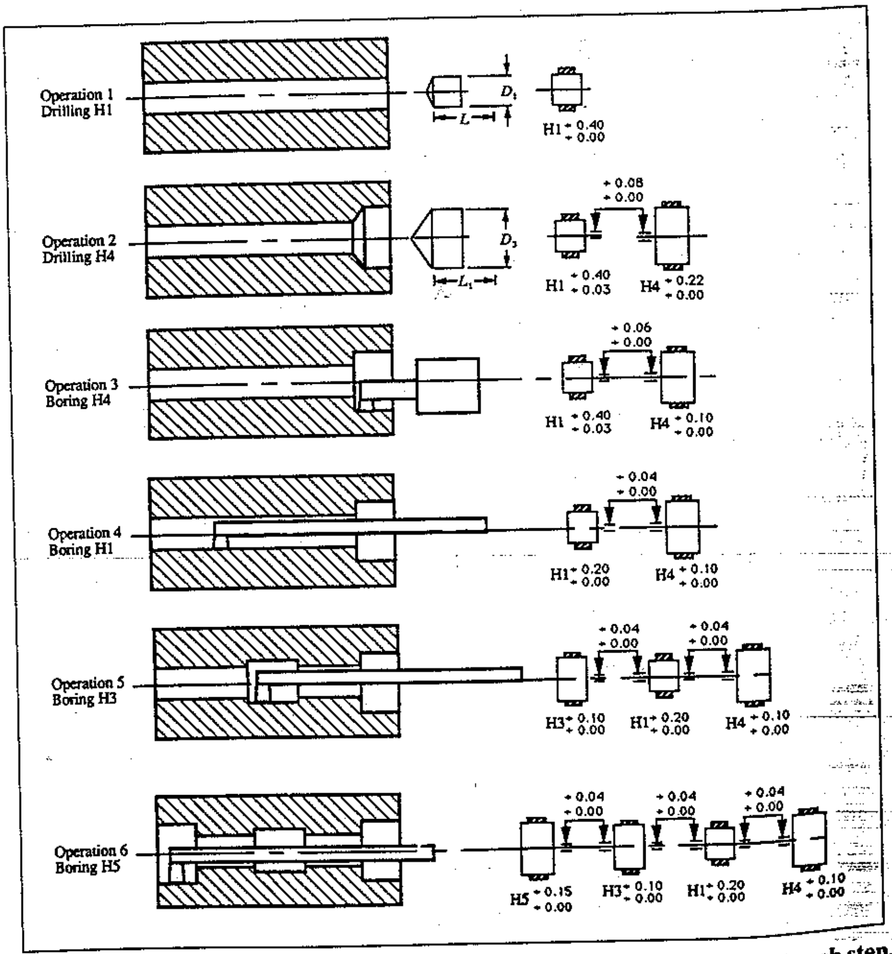

Figure 3. Operation sequence 2 and the machining tolerances produced at each step.