Multi-Objective Process Planning in Environmentally Conscious Manufacturing: A Feature-Based Approach

P. Sheng, M. Srinivasan
Dept. of Mechanical Engineering, University of California, Berkeley, CA, USA

Submitted by S. Kobayashi (1)
Received on January 10, 1995

Summary

Environmental factors have become important in manufacturing planning due to governmental regulations and a growing preference for "green" products. However, planning decisions must also consider traditional dimensions such as production rate and quality. Major issues for environmentally-conscious planning are (1) comparative assessment of waste streams and (2) computational complexity of evaluating multiple processing alternatives. Environmental impact of dissimilar waste streams is analyzed through a scoring system which evaluates factors such as toxicity, carcenogenesis, irritation, flammability, and reactivity. Complexity of processing alternatives is reduced through a feature-based approach, where the component environmental impact is decomposed into "micro" analyses of individual features and "macro" analysis of feature interactions.

Keywords: Machining, Environment

1. Introduction

Due to the increasing regulation of industrial effluents and growing consumer preference for "green" products, manufacturers have begun to explore proactive means of reducing both the quantity and impact of effluents through improved process design and planning. In machining processes, design, setup and operating decisions affect the generation of waste streams such as cutting fluid in liquid, mist and vapour forms, contaminated chips, worn tools and expended energy. The interactions between thermal, mechanical and chemical aspects of the process in waste generation are complex. Decisions in the selection of materials, tools, machining and setup parameters usually have secondary effects beyond the single output variable(production rate or quality) process planners have traditionally tried to optimize.

There has recently been some qualitative studies examining the process level impacts on environmental factors [1,2,3]. In [4] a process model for machining was introduced incorporating analytical descriptions of process mechanics, tool wear, and mass flow of different waste streams. Overall, there are two main issues in environmentally conscious process planning which must be addressed: (1) Evaluation of multiple waste streams emanating from a process and (2) Handling the complexity of evaluating the alternative process paths for an engineered part. First, given equal mass flows of two waste streams, their environmental impacts are not the same. Even for the same substance, waste streams in different phases will have vastly different impacts. These impacts will also depend on site-specific factors such as safety practice, protective equipment, facilities design, machine design and waste handling.

Second, on a planning level, the manufacture of a machined part requires that a sequence of machining processes be performed. There may be several alternatives to produce an equivalent part. In order to fully evaluate the trade-offs in these different alternatives, a set of quantifiable dimensions such as energy consumption, production rate, mass flow of waste streams and quality parameters need to be analyzed at the planning stage. The degree of importance of each dimension may vary between products or plants, depending on the type of operation (bulk removal vs. finishing) and site specific considerations. In [7], a dynamic programming approach was introduced to evaluate multi-criteria trade-offs for process selection based on the above dimensions. As the part design becomes increasingly complex, the network of possible process paths become difficult to enumerate along multiple dimensions. One approach to reducing the computational effort is to decompose the part design into geometric features and evaluate the quantifiable dimensions of each feature through a network optimization analysis of alternative process paths in a micro-plan. This micro-plan can then combined with a macro-plan to evaluate feature interactions. In this manner, the environmental impact of incremental part changes can be efficiently analyzed.

2. Process Planning Approaches

Historically, process planning was focused on Machining Economics, and was based on the derivation of mathematical models of total process cost [8,9]. Operating parameters were chosen based on minimizing cost (Figure 1), with tool life often the dominating factor. One application of this method was for cutting fluid selection [10].

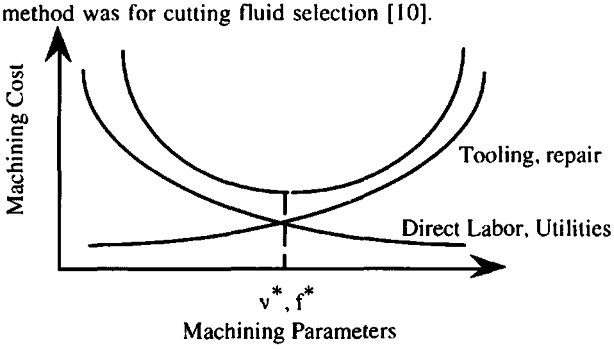


Figure 1 : Variation of Cost with Machining Parameters

While the above methodology was sufficient for analyzing simple production volume and cost tradeoffs, advances in the physical understanding of the process, integration of machine tools and concurrent engineering introduced new dimensions to the optimization problem, such as component quality, flexibility and environmental impact. These contemporary dimensions cannot be easily adapted to machining economics, as many of the effects carry uncertainity, discontinuity or present difficulty in internalizing costs. Therefore a new strategy for process planning is necessary.

The deficiencies of the machining economics approach led to the development of the expert systems approach, based on capturing the knowledge of the machinist in the form of rules. However, this approach lacked information about process physics and required substantial resources even in a limited domain of processes.

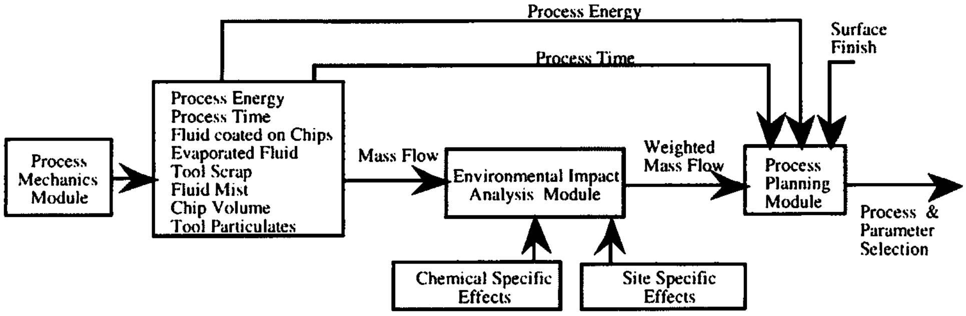


Figure 2 : "Feed Forward" Model Based Decision Making

To incorporate environmental factors into manufacturing decision making, a "feed-forward" process planning procedure can be used (Figure 2). In typical planning problems, the engineer is faced with a finite set of alternative process sequences to produce an equivalent finished part. With the analysis of process mechanics, tool life and fluid flow, process energy, machining time and the mass flow of component waste streams can be estimated. The mass flows are input to the environmental impact analysis module, where the waste streams are scored based on the factors of toxicity, carcinogenicity, irritation, reactivity and flammability. These scores are incorporated with a site specific prioritization scheme to develop "weighted" mass flows which describe environmental impact. Finally, the weighted mass flows, process energy, process time and quality indicators(tolerance, surface finish etc.) are incorporated into the process planning module. This module evaluates these dimensions at a geometric feature level through a system prioritization matrix using the Analytic Hierarchy Process(AHP) [11]. The objectives of this planning scheme are to select an optimal process path and parameters from a set of alternative paths which best reflect the manufacturing priorities between environmental, production rate and quality factors. By using analytical modeling, good estimates can be developed for cases where no past data is available. The computational efficiency is also improved. In the following sections, different aspects of the decision path will be presented in greater depth and an overall process planning strategy will be developed.

3. Process Modeling

At the core of the approach is the process mechanics model. The model is a linkage of analyses of process mechanics, tool temperature and wear, chip formation and cutting fluid flows. Since the machining process involves complex chemical-thermal-mechanical interactions, the effect of one aspect of the process influence the generation of many output parameters. The process mechanics model was derived in [5] for the general case of oblique cutting, resulting in a relationship for process energy as,

$$E=\left(\frac{\cos(\beta_n-\gamma_n)\cos\eta_s\cos\lambda + \cos(\varphi_n+\beta_n-\gamma_n)\sin\eta_s\sin\lambda}{\cos(\varphi_n+\beta_n-\gamma_n)\sin\varphi_n\cos\lambda}\right)\tau_s \text{ Vol}.. \quad (1)$$

where ϕ_n, β_n, γ_n, η_s and λ are the normal shear plane, friction, rake, shear flow and oblique angles. τ_s is the shear strength of the workpiece and Vol is the volume of material to be removed. Tool life can be estimated using models for abrasive and diffusive wear, using a criteria of 0.3mm wear land length as a tool life factor. The number of tools expended can be expressed as,

$$\text{No. of Tools Expended} = \frac{\int_{t=0}^{t=t_{proc}} (WR_A + WR_D)\,dt}{0.3\text{mm}} \quad (2)$$

where WR_A and WR_D are the abrasive and diffusion wear rates determined in [6]. The temperature effect on tool life is also incorporated into the process model. Tool temperatures can be estimated from:

$$T_{Tool} = \frac{q_s + q_r}{\rho c_p V} + T_\infty \quad (3)$$

where q_s and q_r are the heat generated at the shear plane and rake face (assumed to be equal to the mechanical friction energy dissipated), ρ and c_p are the material density and specific heat, and V is the cutting velocity. Given the initial geometry of the workpiece, the volume of chips removed can be estimated. The chip geometry can also be determined given the operating parameters. The cutting fluid exits the process in four forms: liquid recirculated back to the process, liquid coated onto the chips and workpiece, mist released to the environment, and vaporized fluid. The mass of the chip and workpiece-coated fluid can be calculated through analysis of surface tension, while the mass of vaporized fluid is calculated through an energy balance for phase change. Detailed equations for the different output dimensions are presented in [4].

4. Environmental Impact Analysis

Process waste streams (such as cutting fluid mist, vapor and liquid coated on chips, tool scrap, tool workpiece particulates and the chip volume) occur in different states, have different transport mechanisms and different environmental impacts. A common basis of comparison must be established for determining the environmental impact of dissimilar substances. One method is a hazard score which reflects the potential health effects of the waste stream as well as site specific conditions which affect fate and transport mechanisms. A summary of the scheme described in [12] is presented here. The environmental effects are limited to the immediate exposures to waste streams in the vicinity of the process; chronic effects such as soil contamination, atmospheric or waterborne releases to the environment outside the plant are not considered.

A 1x7 hazard vector **H** is developed for each waste stream based on the dose-response of the constituents of the waste stream to the effects of Oral Toxicity(O), Inhalation Toxicity(I), Carcinogenicity(C), Reactivity(R), Flammability(F), Eye Irritation(E), and Dermal Irritation(D) [12]. Each element of the vector represents the potential risk of the waste stream to the particular effect. The fate and transport mechanism of these waste streams varies with local conditions. A quantitative assessement of site-specific effects on health hazards must be made from highly qualitative information. One method of formalizing this judgement is through the Analytic Hierarchy Process(AHP) [11], which develops a set of pairwise comparisons to form a prioritization matrix among the health hazards. A typical matrix is shown in Figure 3. Based on this matrix, a 7x1 site specific vector **F** can be calculated. First a rank value for each row is determined through the relationship:

$$R_i=\left(\prod_{j=1}^{k} X_{ij}\right)^{\frac{1}{k}} \quad (4)$$

where X_{ij} are the elements of the AHP matrix. The elements of the vector **F** are then determined by a simple normalization.

$$\mathbf{X} = \begin{array}{c|ccccccc|} & O & I & E & D & C & R & F \\ O & 1 & 1/5 & 1/10 & 1/30 & 1/2 & 1/20 & 1/20 \\ I & 5 & 1 & 1 & 1/10 & 2 & 1/5 & 1/5 \\ E & 10 & 1 & 1 & 1/6 & 2 & 1/4 & 1/3 \\ D & 30 & 10 & 6 & 1 & 15 & 2 & 3 \\ C & 2 & 1/2 & 1/2 & 1/15 & 1 & 1/5 & 1/8 \\ R & 20 & 5 & 4 & 1/2 & 5 & 1 & 1 \\ F & 20 & 5 & 3 & 1/3 & 8 & 1 & 1 \end{array}$$

Figure 3: Example of a Site Specific Prioritization Matrix

$$F_i = \frac{R_i}{\sum_{i=1}^{k} R_i}, \; i=1,..,k \tag{5}$$

For Figure 3, the $\underline{\mathbf{F}}$ vector is determined to be $[0.01 \quad 0.05 \quad 0.07 \quad 0.43 \quad 0.03 \quad 0.21 \quad 0.20]^T$. The final health hazard score (HHS) for a particular waste stream is determined by HHS = $\underline{\mathbf{H}} \cdot \underline{\mathbf{F}}$. This score is then used to weight the particular waste stream and the total weighted mass of the waste streams is,

$$m_w = \sum_{i=1}^{n} (1 + HHS_i) m_i \tag{6}$$

where n is total number of waste streams considered and m_i is the raw mass of the i^{th} waste stream.

4.1 *System Prioritization*

In order to evaluate alternative processes over multiple dimensions, it is necessary to prioritize them based on production planning needs. An example of a system prioritization is shown in Figure 4.

$$\begin{array}{l|cccc|} & \text{Process Energy} & \text{Process Time} & \text{Quality} & \text{Weighted Mass} \\ \text{Process Energy} & 1 & 1/6 & 1/4 & 1/2 \\ \text{Process Time} & 6 & 1 & 3/2 & 3 \\ \text{Quality} & 4 & 2/3 & 1 & 2 \\ \text{Weighted Mass} & 2 & 1/3 & 1/2 & 1 \end{array}$$

Figure 4: Example of a System Prioritization Matrix

The Analytic Hierarchy Process (AHP) is then used to determine the 1x4 vector ($\underline{\mathbf{A}}$) of relative weights. For Figure 4, the $\underline{\mathbf{A}}$ vector is (.07,.45,.30,.18). The overall utility of the manufacturing system can be written as,

$$Util = A_1\left(1-\frac{E}{E_b}\right) + A_2\left(1-\frac{t}{t_b}\right) + A_3\left(1-\frac{q}{q_b}\right) + A_4\left(1-\frac{m_w}{m_b}\right) \tag{7}$$

where E_b, t_b, q_b, m_b, are the baseline outputs chosen from the minimum values of the those variables in all alternative process paths. Since the AHP weights are dimensionless and there could be orders of magnitude differences in the process outputs, the baseline values normalize the outputs while determining the utility.

5. Feature Based Planning

Features are essentially geometrical entities which could also represent manufacturable forms. Research in features has mainly concentrated on feature based design on one hand and feature extraction and geometric reasoning algorithms on the other hand [13, 14]. A feature based design environment is based on the premise that designers can specify a part in terms of its meaningful geometric or manufacturing features. Once these manufacturable features are obtained, process planning is done by specifying processes that can manufacture these individual features. Hence the final process plan consists of sub plans for the individual features.

Each feature is evaluated against the objectives for the process and parameter selection. Regardless of part complexity, the process planning is incremental and the computation is always within bounds. Since feature based design lends itself readily to a CAD interface, it allows our decision making model to be interfaced with such an environment.

The two main steps in feature based process planning are Macro and Micro planning [15]. At the micro level, different process paths for each feature are generated. The appropriate process path and the associated machining parameters, based on the decision model of Figure 1, are selected. At the macro level, interactions between features and its effects on the process plan are considered.

5.1 *Micro Planning*

Associated with each feature is a network with the branches representing different production paths for generating that feature(Figure 5).

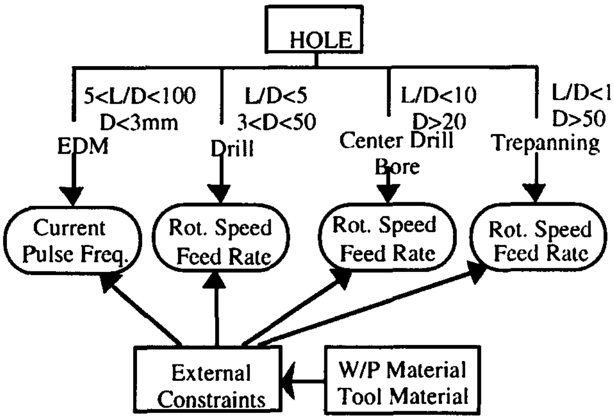


Figure 5: Process Network associated with a hole

At the first level, based on the geometry of the feature (diameter and aspect ratio in Figure 5), all the feasible process paths are selected. Associated with each process path, are ranges of allowable process parameters for that process. These ranges are first evaluated with respect to external constraints, (such as a minimum required production rate) which will fix some process parameters. For each path, the best parameters from within the specified ranges are selected by maximizing the utility function (Equation 7). The process path with the highest utility is then chosen. To illustrate the micro-planning concept, consider the input feature to be a through hole of dimensions D = 35 mm, L=70 mm, to be produced in 4340 Alloy Steel using a HSS tool. From Figure 5, the feasible processes are Drilling, Center Drilling/Boring. Given the combination of tool and workpiece materials, the ranges of feeds and speeds can be set around the median values defined in [16] as: .01-.40 mm/rev for the feed, and 5-40 m/min for the rotational speed. In the Center Drilling and Boring operations, the diameter of the pilot hole is assumed to be 30 mm and a 2.5 mm depth of cut is taken by the boring tool.

Effect	H	F	Effect	H	F
I	1.15	.05	F	1.25	.20
O	3.10	.01	D	5.90	.43
R	7.70	.21	E	8.55	.07
C	2.90	.03	-	-	-

Table 1: H and F vectors for fluid waste streams

Table 1 shows the $\underline{\mathbf{H}}$ and $\underline{\mathbf{F}}$ vector for a typical oil based cutting fluid as determined in [12]. The health hazard score (HHS = $\underline{\mathbf{H}} \cdot \underline{\mathbf{F}}$) is 5.18. The health hazard score for the waste stream of solid chips is 0.0. An example of the total weighted mass calculation is shown for the drilling process in Table 2.

Assuming all alternatives produce the feature with acceptable quality, the trade-offs between the two processes are apparent (Table 3). Using the system prioritizations of

Figure 4, drilling is chosen over center-drill and bore, as it has a greater utility value. If we impose an external constraint on the machining time to 30 sec. then setting the feed to .4 mm/rev, a new set of output values as shown in Table 4 are obtained. In this case the center-drill and bore is chosen over drilling.

Waste Stream	Raw Mass (kg)	HHS	m_w
Coated Fluid	.56	5.18	3.46
Evap. Fluid	.20	5.18	1.24
Metal Chips	.53	0.00	.53
			$\Sigma\, m_w$=5.23

Table 2: Weighted Mass Calculation for Drilling

Process	Drill	Drill and Bore
Rot. Speed (m/min)	88	33
Feed Speed (mm/rev)	.4	.4
Energy (MJ)	.79	.62
Weighted Mass	5.23	4.97
Process Time (min)	1.34	1.86

Table 3 : Process Outputs

Process	Drill	Drill and Bore
Rot. Speed (m/min)	88	33
Feed Speed (mm/rev)	.4	.4
Energy (MJ)	.79	.62
Weighted Mass	6.83	4.97
Process Time (min)	.50	1.86

Table 4 : Process Outputs under external constraint

5.2 Macro Planning

Micro Planning concentrated on process selection for a single feature and ignored interactions between features. Two features interact when their machining volumes are nested or they intersect [13]. With nested features, the actual feature becomes modified and research on these modifications has concentrated primarily on geometric reasoning. However with the modified features, the decision model generates different outputs. Hence process sequencing becomes an important macro planning issue.

Consider a part consisting of three types of features: a pocket, a hole and a finished planar face. From the figure it is apparent that the hole is nested within the pocket and the planar face. If the micro plan generated drilling, end milling and face milling for machining the three features, different process sequences are analyzed for the process outputs(Figure 7).Assuming that the part is manufacturable in all the three sequences, the actual feature being machined by the same process in different sequences is different. For example, insequence 1 the hole feature has a length of 90 mm while in sequence 2, it has a length of 140 mm. Hence the volume of all the three features changes depending on the sequence. The difference in process outputs can be easily understood based on the following analysis. Let e_i and e_j be the specific cutting energy for two processes i and j. Let V_i and V_j be the volume of material removed in the two processes in Sequence 1. The total energy E_1 is,

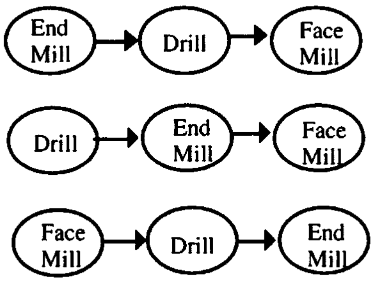


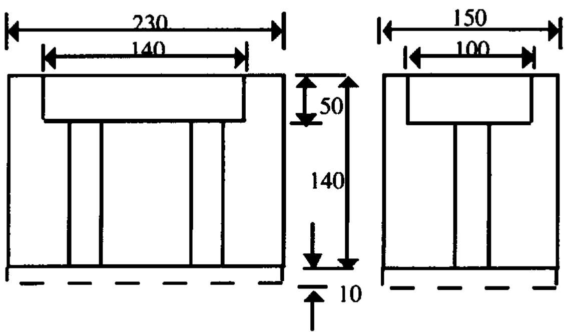
Figure 7: Three Process Sequences

$$E_1=e_iV_i+e_jV_j \qquad (8)$$

In Sequence 2, the volume of material removed by process i is increased by an amount q and the volume of material removed by process j is decreased by q. Hence the total energy E_2 can be written as,

$$E_2=e_i(V_i+q)+e_j(V_j-q)=E_1+(e_i-e_j)q \qquad (9)$$

If $e_i>e_j$ then sequence 1 has a lower process energy. The process outputs for the 3 different sequences is shown in Table 5. Again, given the prioritizations in Figure 4, sequence 1 would be chosen as the optimal compromise between energy, weighted mass and process time, as it maximizes the utility. Once the sequence is chosen, another iteration of microplanning is needed to set the optimal process parameters. In the second iteration the process network for each feature in the sequence will consist of only one process path that was selected at the initial microplanning iteration.



(a) Front View (b) Side View

Figure 6 : A Sample Part

Sequence	1	2	3
Energy (MJ)	4.7	5.5	4.8
Weighted Mass	15.3	16.4	14.4
Process Time (min)	12.1	10.2	13

Table 5: Process Outputs for different sequences

6. Conclusion

Model-based approach to process planning provides a rapid, robust estimation of energy and mass flows. One important issue is modeling error. In an ideal situation, the model information must be integrated with plant process data to create a closed loop decision making model. Measured data would include sampled aggregate plant-wide information (such as coolant replenishment levels), as well as process information collected in real-time (such as tool-wear estimates).

Another area of uncertainity is in the environmental scoring. The data for many factors are difficult to obtain and often conflict from study-to-study. In [12], the uncertainty due to incomplete environmental information is addressed in order to increase the robustness of using the health hazard score. The main advantage of using the AHP matrix is the relative robustness of the final decision to the elements of the matrix.

This decision model can be used as part of an overall process planning module that accounts for fixturing, and other heuristical information that must be coded in a rule base. It can also be used as a 'green' advisor providing real-time information on the environmental impact of the manufacturing process at the design stage. A feature based CAD interface is currently being developed which can be integrated with an open architecture machine tool controller [17].

7. Acknowledgements

This work was supported by the members of the Consortium on Green Design and Manufacturing at the University of California, Berkeley.

8. References

[1] Byrne,G. and Scholta, E., "Environmentally Clean Machining Processes-A Strategic Approach," *Annals of the CIRP* , Vol. 41, 1993.

[2] Olsen, W.W., and Sutherland, J.W., "Environmentally Conscious Manufacturing,"*1994 Japan-U.S.A Symposium on Flexible Automation*, Vol. 3, pp. 1035-1042, 1994.

[3] Howes, T.D., Tonshoff, H.K.,and Heuer,W., "Environmental Aspects of Grinding Fluids," *Annals of the CIRP*, Vol. 40/2, 1991.

[4] Munoz, A.A.,and Sheng, P., "An Analytical Approach for Determining the Environmental Impact of Machining Processes," *Journal of Materials Processing Technology*, to appear.

[5] DeVries,W.R., Analysis of Metal Removal Processes Springer-Verlag, NY, 1992.

[6] Kramer, B.M., and Von TurKovich, B.F., "A Comprehensive Tool Wear Model," *Annals of the CIRP*, Vol. 35, No. 1, 1986.

[7] Sheng, P., Worhach, P.,and Gunc, P., "A Network Optimization Framework for Environmentally Conscious Process Planning and Product Design," ESRC Technical Report 94-3, *Engineering Systems Research Center*, University of California at Berkeley.

[8] Gilbert, W.W., "Economics of Machining," Machining Theory and Practice, *American Society for Metals*,Cleveland, 1952.

[9] DeVries, M.F., "Machining Economics-A Review of the Traditional Approaches and Introduction to New Concepts,"*American Society of Tool and Mfg. Engineers*, #MR 69-279, pp. 435-442, 1969.

[10] Shaw, M.C., Metal Cutting Principles, Oxford University Press, 1984.

[11] Saaty, T.L.,The Analytic Hierarchy Process, McGraw-Hill, 1980.

[12] Srinivasan, M., Wu, T., Sheng, P., "Development of a Scoring Index for Evaluation of Environmental Factors in Machining Processes: Part1 - Formulation," *Transactions of NAMRI/SME*, Vol. 23, 1995.

[13] Anderson, D.C., and Chang, T.C., "Geometric Reasoning in Feature Based Design and Process Planning," *Computers and Graphics*, Vol. 14, No. 2, pp. 225-235, 1990.

[14] Shah, J.J., "Assessment of features technology," *Computer Aided Design*, Vol. 23, No. 5, June 1991.

[15] Sarma, S.E., Schofield, S., Stori, J., Wright, P.K., MacFarlane, J., "Rapid Product Realization from Detail Design," *Computer Aided Design*, to appear.

[16] Machining Data Handbook, Institute of Advanced Manufacturing Sciences Inc., 3rd Edition, 1980.

[17] Greenfeld, I., 1989, "Open-System Machine Controllers - The MOSAIC concept and implementation," *Trans. ACM*, Vol. 18, pp 91-97.