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INTEGRATED PRODUCT AND PROCESS DESIGN (IPPD): FOR RAPID, MORE AFFORDABLE PARTS/SYSTEMS USING KNOWLEDGE-BASED ENGINEERING METHODS

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13. ABSTRACT

Our efforts have focused on an architecture for the development of a design and modeling framework for knowledge-based engineering. Emphasis has been placed on generic methods applicable to both defense and commercial electro-mechanical systems. This report will address both the results of the small business innovation research program and subsequent investments by Ford Motor Company, Lockheed-Martin and other system manufacturers which have focused on engineering analysis, geometric modeling, meshing, visualization, and simulation methods. The report will also highlight the leveraging of in-house federal laboratory research programs, specifically, materials process design research within the Wright Laboratory, Materials Directorate. All of the above investments and interactions have contributed toward further advancing and applying knowlege-based engineering methods for integrated product and process design.

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1. Executive Summary

Our efforts have focused on an architecture for the development of a design and modeling framework for knowledge-based engineering. Emphasis has been placed on generic methods applicable to both defense and commercial electro-mechanical systems. This report will address both the results of the small business innovation research program and subsequent investments by Ford Motor Company, Lockheed-Martin and other system manufacturers which have focused on engineering analysis, geometric modeling, meshing, visualization and simulation methods. The report will also highlight the leveraging of in-house federal laboratory research programs, specifically, materials process design research within the Wright Laboratory, Materials Directorate. All of the above investments and interactions have contributed toward further advancing and applying knowledge-based engineering methods for integrated product and process design.

Today's global market requires existing enterprises to compete in an environment that is changing at an ever-increasing pace. Such a dynamic marketplace requires making quick decisions wherein customer demands dictate rapid response. Competing demands and numerous changes will result in prolonging the development process.

The product-process engineering cycle (i.e., the design of a products shape, performance, manufacture, etc. . . .) is a complex, highly interactive, and time-consuming process. Customer specifications and considerations such as cost, performance, weight, accuracy, life, and other aspects must be addressed to bring about an effective product design. Often, the multidisciplinary nature of product-process design requires expertise ranging from control engineering to mechanical design, system simulation, structural and thermal analyses to address the breadth and complexity of a product. Design changes (i.e., relative to dimensions, tolerances, materials, process constraints, etc.) and rework procedures delay final production and market deployment. Rework procedures can be very costly especially if revisions are introduced late in the engineering cycle.

On the other hand, new ideas and/or new product technologies are often introduced through the product-process engineering cycle. It is during this stage that alternative materials and processes are discovered and tested in an attempt to enhance product functionality and to reduce production cost. Therefore changes may be encountered which will both benefit the product performance but increase the engineering cost and/or introduce production delays. Enabling the investigation of these alternative designs, materials, and processes while minimizing impacts on development and/or production time and cost is the ultimate goal.

Alternative materials and processing investigation and analysis not only involves new designs, but the design of replacement parts for existing and/or aging systems, in the case of aircraft systems. The key issue is the incorporation and application of prior or existing knowledge into new designs to benchmark and explore alternative materials and processes without a protracted classical design process based upon iterative design-evaluate-revise steps which are time consuming and fraught with error.

From the above discussion one can see the need for a design environment framework that is capable of capturing and exploiting an integrated product-process strategy. Such a design environment tracks the strategies employed by the different processes involved and any change in a design automatically triggers and updates the related information associated with the relevant processes while conserving the solution strategy that already has been used. The modeling of alternative product-process designs while tracking their dynamic associativity will lead to major savings in the product development time. This will enable the investigation of alternative materials and processes to lower the product production cost while enhancing performance.

This framework will be the basis for the development of a Knowledge-Based-Engineering (KBE) system for feature-based integrated design, to include material specification, manufacturing/inspection process planning, adaptive meshing, and finite element modeling/analysis. The KBE system will incorporate a unique underlying object-oriented part model for representing component geometry and material, in addition to process plan(s), and finite element models. It is the efficiencies of the user interface response times and computational tractiveness afforded by an integrated part model which will promote the needed multidisciplinary interaction among design engineers to reduce costs and improve performance.

The results of this small business innovation research program will be addressed in greater detail in subsequent sections of this report and include:

- A unique system architecture for concurrent, multidisciplinary product-process design and production.
- A framework for a parametric, feature-based, integrated part model to support an interactive design environment.
- An integrated product-process design system to automate the generation of the process plans based upon design features, part materials, and processing capabilities and constraints.
- Automated generation and simulation of the machining process plans by integrating the manufacturing process and the part shape, to include cost based on the tool cost, manufacturing time, setups, etc.
- An integrated system to investigate alternative materials and processes and their impact on the part shape, part performance, and material integrity.

2. Introduction and Background

Contemporary product design and process development are based on an iterative specify-evaluate-revise approach described in Figure 2-1. This approach is a cycle that is often time intensive. The engineering of a product incorporates numerous stages involving design specification, manufacturing planning, finite element modeling and analysis (FEM/FEA), inspection planning, etc.

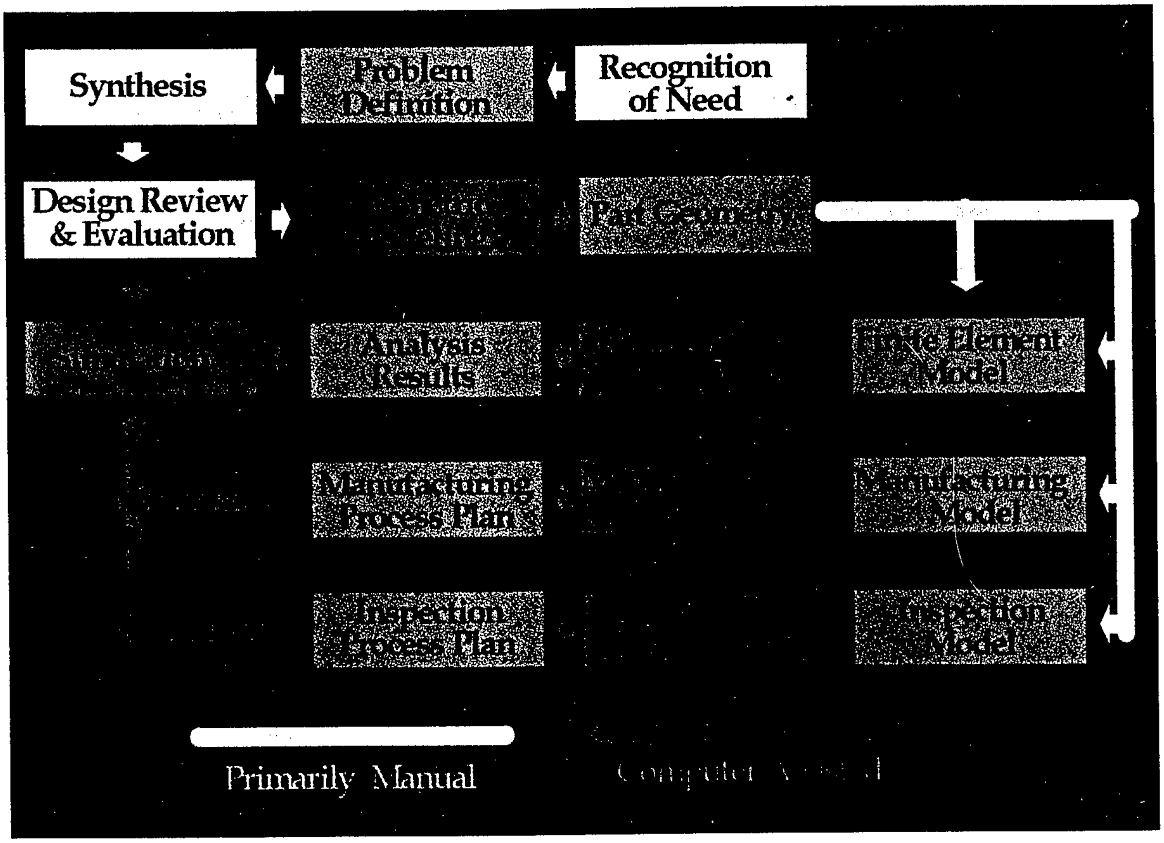


Figure 2-1. Design to Production Planning Cycle

For small quantities or lot sizes (1-25 parts), the product design and process planning steps account for an inordinate share of the overall development cycle. An integrated system for concurrent, multidisciplinary design is needed to increase the design-through-production efficiencies. The system should enable the user to interactively design and plan alternative processes. An example process is machining, which is both pervasive in use and often a benchmark for comparison of alternative processes. To enable integrated product-process design for the machining process, a process plan generator must entertain a number of design considerations related to setup generation, feature sequencing, fixturing, tooling, tool path logic, and machining parameter computation.

There are a number of automated systems for milling or drilling simple features, but these systems generally are not geometry driven in terms of selecting the best tool, part orientation, and computing a minimum numbers of cuts, tool paths, while evaluating various types of tool-part offsets and collisions. These existing systems address the automation of the process plan by generating a list of the machining operations, sequence and feed, speed and depth data to cut a single feature. The user input is a feature type and specification entered in a table format. The capability of these systems is limited to a prescribed library of features and do not offer any assistance regarding setup generation, fixturing, or any other process planning criteria. Yet, there are some systems which have been successful in generating setups and related fixture information for machining a part using a part description entered by the user in a text format with a special language and syntax. The reasoning behind these systems is based on the variant approach to comparing, retrieving, and modifying similar pre-stored process plans. In addition to the limitation of the pre-stored patterns, existing systems do not offer the bi-directional propagation of constraints needed in an integrated product-process design system.

The predominant approach employed by CIM (Computer Integrated Manufacturing) vendors is oriented towards automating tool path generation from the part geometry created by a CAD system. These systems produce a primitive cutting plan by mapping the tool path to follow the contour of a surface. Even though they may handle complex surfaces, these systems offer little or no assistance in the selection of the tooling and machining data specifications. In addition, they tend to rely heavily on user interactions for isolating and sequencing the surfaces to be cut, therefore, complicating the process plan generation and tool path logic of even simple parts.

Translating the geometry of a part and extracting the data for automating the process plan and fixturing of customized parts is a challenge. An automated planner for extracting the manufacturing features from the part geometry, generating and sequencing setups, and recommending the fixtures and fixture locations is the optimum solution. This system should also be integrated in a user friendly free-form feature-based design environment, enabling the user to easily design parts with complex geometry. The AML architecture described herein addresses the above limitations and supports an environment for interactive product-process design of machined components. The process plan incorporates the selection of setups, their sequence, tooling, and all the machining data for cutting the part, reflecting the part geometry, the part material characteristics, and the machine selection based upon available machining resources. In addition, the user can interactively view and edit the production plan to observe the intermittent effects of the product-process design and/or modifications therein, i.e., system automatically validates the changes and reconfigures the process plan reflecting the user modifications.

AML supports a sophisticated feature-based design environment, enabling the user to interactively design parts of varying geometric complexity. Features are basically descriptive classes of shapes with position and dimensional constraints that enable the transfer of a part model without transferring the geometry instance. Features are part model objects which incorporate geometric relations and constraints in addition to non-geometric attributes for reasoning about the part representation to automatically generate the process plan. The FBDE (Feature Based Design Environment) within AML is representative of the capabilities of most parametric CAD systems, with advanced tools for interactive feature dimensioning, positioning, and orientation specifications. AML also supports a geometric reasoning algorithm to assist in the feature interpretation and instantiation. AML is unlike other parametric CAD systems in that it employs an open-architecture for coupling to other CAD systems.

Existing CAD systems have not addressed many of the issues related to product-process design integration. They have tended to rely heavily on user specifications to guide the tool selection, machining parameters computation, and the generation of the tool path. To address these issues, AML incorporates a unique underlying object-oriented part model for representing the part geometry and material, in addition to the part process plan(s) and finite element model. This single integrated part model (Figure 2-2) simplifies part representation and enables bi-directional constraint propagation across multiple design disciplines offering a true concurrent engineering environment integrating product-process design with materials specification, and modeling.

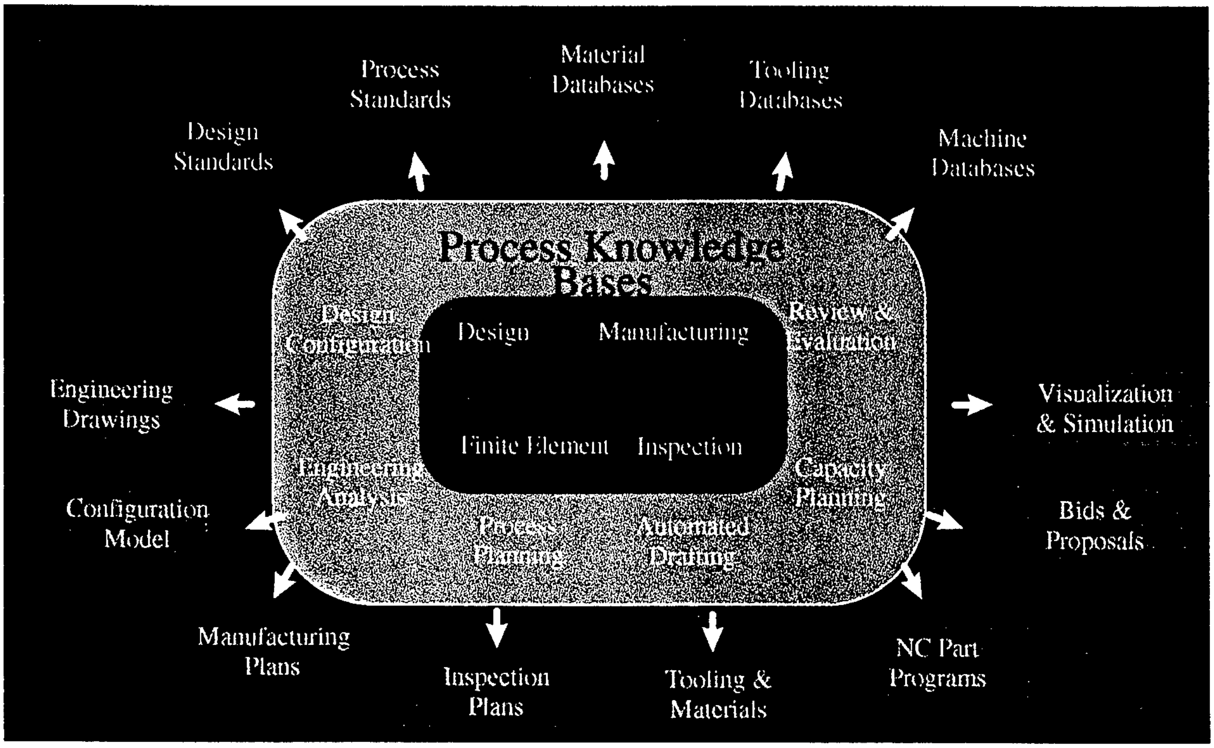


Figure 2-2. AML's Unified Part Model

3. Objective and Approach

Process planning is among the most important functions of a manufacturing system. Starting with the part specifications and geometry, the process plan for machined parts requires the preparation of an outline that describes all the machining setups, the intermediate part geometry, the detailed machining operations including tooling grades and geometry, the machining data, and finally the NC part program to cut the part. Whether a generic process such as machining, or a rather Air Force-unique process such as eddy current inspection of engine components for fatigue crack detection, it involves the preparation of a process outline, i.e., which describes the inspection setups, the probe specifications, the probe path and travel speed based on the part features, surface geometry, part material, selected/available probes and the inspection criteria.

3.1 Feature Based Design User Interface

To enable a fully bi-directional product-process design capability, a parametric, free-form, constraint driven, feature-based design environment is needed. Critical to an open architectured design environment is the AML supported 3D mixed dimensional modeling (wire-frame/solid/surface mixed modeling). AML enables the user to create a free-form feature and parametrically associate its dimensions and orientation with other features. The user can interactively add attributes to the features, in addition to constraints and relations, while associating both geometric and non-geometric properties.

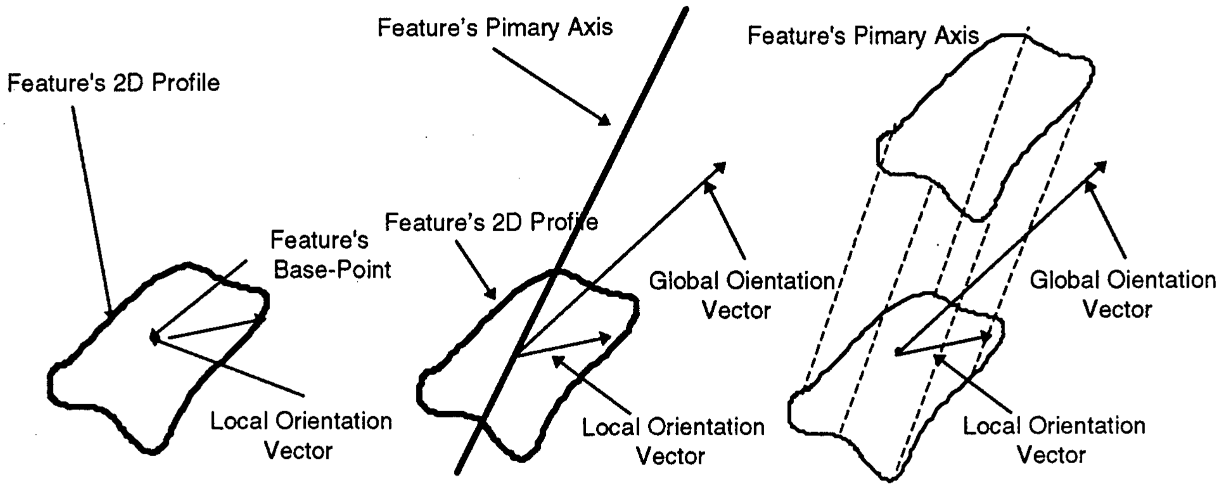


Figure 3-1. Feature Instance

AML offers the user an interactive design environment with unmatched ease of use. The part design is simplified by implementing a powerful and unique approach for feature instantiation. An icon-based graphical user interface enables the creation, editing, and modification of part geometry. To create a free-form feature such as a pocket with a generic base profile, the user first starts by creating the 2D profile as the feature-base, and selects a base-point (Figure 3-1). AML offers a number of tools to assist in the creation of the profile. Once a profile is created, the user selects two 3D points, PT1, and PT2 (Figure 3-2). The feature base is translated from the base-point to PT1. The two 3D points PT1 and PT2 form the feature's primary axis (Figure 3-2). For the feature orientation, the user will select a point in the plane of the profile to create the local orientation vector. Another 3D point is selected in the 3D space to form the global orientation vector. The system automatically computes the translation and rotation matrices to orient the feature. The feature is rotated about the primary axis to set the local orientation vector and the global orientation coplanar. AML also offers a number of tools to assist the user in the interactive selection of the points and vectors. Furthermore, AML automatically configures the bounding surfaces of the features depending on the intersections of the feature surfaces with the part geometry (Figure 3-2), and the attribute "blind-feature" or "through-feature." Another unique characteristic of AML is the capability to validate the geometry to check the consistency of the features and their interactions.

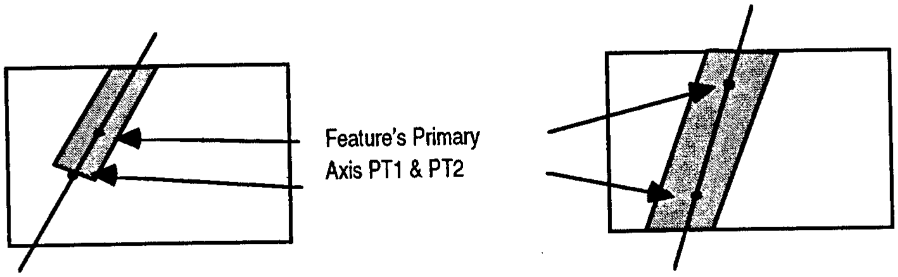


Figure 3-2. Front View of the Instantiation of the Blind-Feature vs. Through-Feature

Feature Translation, Re-Dimensioning, Simplification

AML's single underlying object part model enables the engineers from the different disciplines to interact simultaneously with the different part representations, e.g., emphasizing manufacturing, inspection, or analysis information associated with the part geometry. For manufacturing planning part design features are interpreted as manufacturing features before generating the manufacturing process plan or as inspection features for inspection planning. Similarly the part design model is translated into a finite element model for finite element analysis.

Re-dimensioning is a consequence of the interpretation of a part geometry from a machining perspective. The dimensions of the manufacturing features depend on the feature sequence. Figure 3-3 illustrates the different possible interpretations when positioning three pockets to be machined.

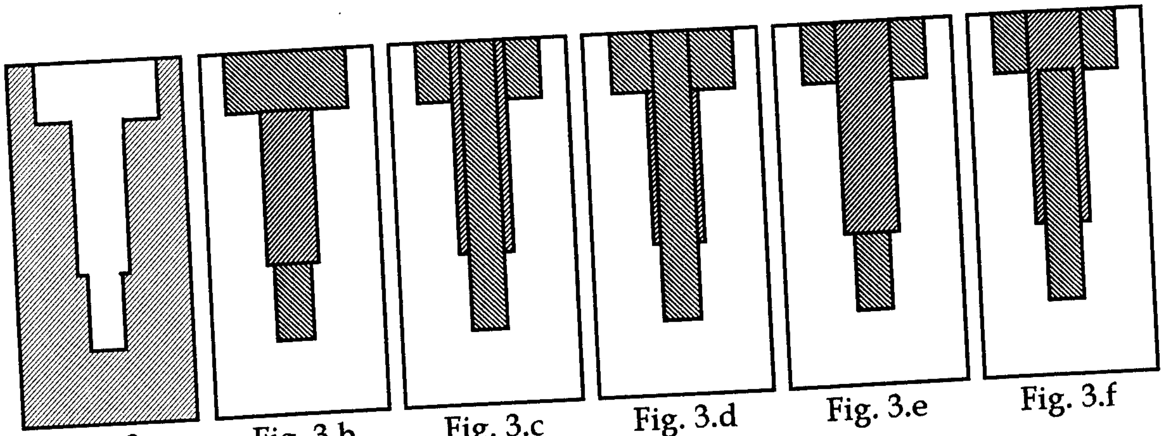


Fig. 3.a Fig. 3.b Fig. 3.c Fig. 3.d Fig. 3.e Fig. 3.f

Figure 3-3. Re-Dimensioning Interpretations

Figure 3.a shows a cross section of a part with three intersecting pockets as specified in the design representation. Figures 3.b through 3.f, illustrate the different interpretations of the same three features with a different instantiation sequence and different dimensions. The geometrical reasoning engine within AML assists the user in sequencing these features as illustrated in the figures above. When the manufacturing sequence differs from the design sequence the system will automatically compute the part feature dimensions. This methodology enables the user to easily modify the product design, via the FBDE, without resorting to part redesign as required by existing CAD/CAM or CIM systems.

3.2 Process Planning for Machined Parts

AML incorporates an advanced constraint-driven geometrical reasoning engine for parameter extraction and relations/constraints specification. AML generates a complete detailed machining process plan based on the part features characteristics (dimensions and tolerances). The machining plan includes the following details and specifications:

- Part geometry before and after each setup
- Intermediate part geometry after removing (machining) each feature within each setup

- A detailed list of operations for machining each feature (including cutting dimensions, speeds, feeds, horsepower, material removal rate, etc.)

- Tooling for each operation including alternative tooling
- A feasible sequence for machining operations for the different features within the same setup

Based upon process constraints, material characteristics, tooling and machine capabilities and availability, the user can inquire about alternative process plan specifications. The uniqueness of the AML approach is that the process plan is based on the part geometry. Previous attempts to automate the machining process plan required the user to describe the part features in a text format. That could become tedious and time consuming, notwithstanding the fact an expert machinist is required to use the system. In addition, AML employs a unique method for translating design features into manufacturing features to extract the part description for the automation of the process plan.

The part design/geometry is basically a description of the geometry in terms of the starting geometry (stock) and the "design features" with their associated dimensions and orientations. In machining process planning, the interpretation of the same geometry is different. An equivalent part description is required to accommodate different manufacturing interpretations of the same part geometry (design). Extracting the manufacturing information from the part design specifications is required to produce the process plan. The design features are translated into manufacturing features to compute the information needed to automate the machining process plan. To achieve the goal of automating process planning the following architecture was implemented:

Design Branch
    Design Profiles
        .
        .
    Design Features
        .
        .
Manufacturing Branch
    Sequence 1
        Manufacturing Feature 1
            Machining Operations
            Tool-Path
        .
        .

3.2.1 Design Feature Translation

A design feature is associated with one or several manufacturing features depending on its attributes. When a feature is translated, in addition to the machining attributes, a number of surface and vector objects are created. These objects are associated with the feature's type, dimensions, and orientation. These objects reflect the tool approach direction and orientation in addition to the appropriate cut-in surfaces. The manufacturing features are the basis for the machining setup generation.

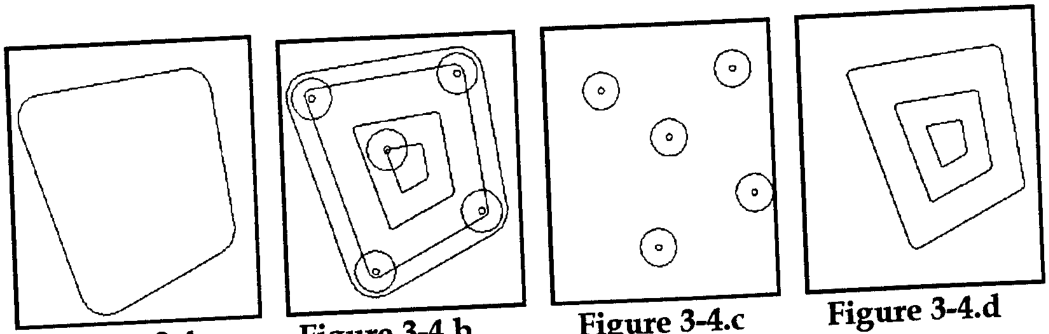


Figure 3-4.a Figure 3-4.b Figure 3-4.c Figure 3-4.d

Figure 3-4. Profile Design of a Pocket

Figure 3-4.a illustrates the profile design of a pocket. Figure 3-4.b illustrates the manufacturing features superimposed to cut the pockets. The manufacturing features shown in Figure 3-4.b and Figure 3-4.c are the four relief holes at the center of each corner and another for clearance to allow for the entrance of the rough end mill. Each hole is preceded with a center-drill feature. Figure 3-4.d illustrates the milling features for roughing and finishing the pocket.

3.2.2 Manufacturing Features

A manufacturing feature is associated with a set of machining operations, related to milling and hole making. Manufacturing features are also associated with certain geometrical constraints related to the part geometry before and after the operations. These constraints are related to the tool access, the part geometry (open-pocket vs. closed-pocket), and machining capabilities (coolant available), etc. Depending on the bounding surfaces, part dimensions, and other characteristics, a design feature is translated into a number of manufacturing features, each representing one or more machining operations.

3.2.3 Machining Operations

Machining operations can be divided into three general categories: Holemaking, Milling, and Turning. The machining operation associated with each category is identified with an associated "object" and specification. For example, among these operations are Center Drilling, Reaming, Boring, etc. With each operation certain requirements must be satisfied. These requirements are related to part geometry, machine capability, material properties, and tool standards, in addition to other machining criteria.

3.2.4 Tooling and Machining Data

The machining part model is basically an enhanced object structure representation in terms of the machining features. Depending on a feature's dimensions and available machining capabilities, the machining operation sequence for each manufacturing feature is generated. The tooling criteria selection is based on the machining capabilities, speed, feed, horsepower, operation, part material, and tooling standards. The tooling data is stored in files, this allows the user to add/remove tools from the tool bin by simply editing a file. Material information is also stored in a file, adding or removing a material is done by editing the materials file and the speed-feed file.

3.2.5 Features Sequencing , Re-Dimensioning, and Machining Parameter Extraction

Manufacturing feature sequencing and feature re-dimensioning are two interconnected problems. Within each setup, a preliminary machining sequence is generated for the intersected features. This machining sequence determines the order of operations for machining the features. It is important to identify intersecting features and generate a near optimum preliminary machining feature sequence with the appropriate dimensions for each feature. The dimensions of the manufacturing features can be different from the associated design feature dimensions as specified by the designer. The dimensions of the manufacturing features are computed based on the associated design features and the manufacturing feature sequence.

3.3 Eddy Current Inspection Planner

The AML architecture also supports the automation of inspection process plan generation. The process plan specifications are based on the part feature surfaces, the part material and the inspection criteria. Starting with the part feature geometry, AML generates a detailed inspection plan including the part inspection program code. The example here is Eddy Current (EC) inspection planning and includes the following details and specifications:

- Part inspection setups
- Features/surfaces within each setup
- Setups sequence
- Detailed inspection operations for inspecting each feature and/or surface (travel speed, probe local/global position and orientation, rpm, etc.)
- Probe selection for each operation including alternatives
- Feasible sequence for the inspection operations of the different features/surfaces within the same setup

Existing equipment is expensive, difficult to program and slow. An EC inspection scan plan for a part could take more than six months to generate. This task is primarily done with little or no automation. In addition, probe wear is a problem due to the difference in the part geometry specification and the actual part. A part that has been installed in the field could be slightly deformed due to applied stresses and deposit of foreign material. This deviation could lead to abnormal wear on the probe when it is in contact with the surface during inspection.

Based upon feature surfaces, material characteristics, EC machines, probes, and inspection processes capabilities and constraints, the AML automated inspection planner generates the specification of the scan plan. Alternative plans are also generated when requested. The system incorporates a constraint manager that enables the user to specify a set of constraints and criteria for alternative plans and tooling recommendations. For example, the user can limit the number of probes to be selected due to unavailability or cost and require the planner to generate alternative plans. The planner also generates a feasible sequence for inspecting the part features/surfaces within a setup to minimize probe travel and probe changes.

The system employs a unique method that translates the design part model into inspection features to extract the part description for the automation of the inspection process plan. After the user selects the feature(s) she/he wish to inspect, the system automatically generates the inspection plan associated with inspecting each of the selected design features.

3.3.1 Machining/Inspection Tool/Probe Path Logic

The AML architecture and development of a geometrical reasoning engine for tool path planning has been researched and implemented. Based on the part geometry, material characteristics and associated process limitations a process plan is generated. In machining the plan includes information on the tool grades, tool geometry, and the machining data. The tool path generated incorporates the recommendations of the process planner and AML cross correlates the tool body shape with the part's initial and final geometry and orientation along with the machine's capabilities (number of axis, travel capabilities) to produce a feasible path logic. When generating the tool path, design alternatives are considered for optimizing the tool travel in addition to surface integrity. The figure below illustrates a tool path computed by the path generator optimizing tool travel.

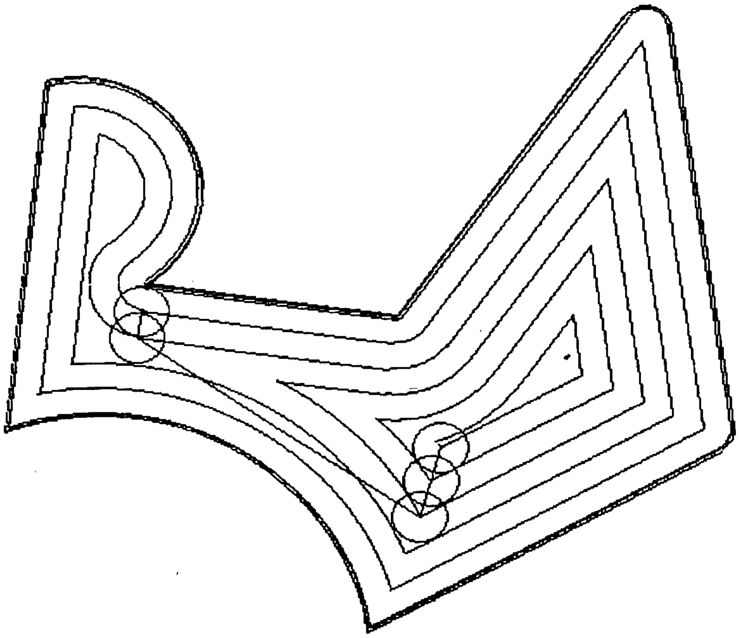


Figure 3-5. Island Profiling

Since AML supports model unification that incorporates dynamics and associativity among potentially differing representations (design, machining, analysis) of the part model, changes to the design feature(s) are automatically propagated to the manufacturing feature(s) and the tool path associated with these changes. The user need not maintain three different models, because in AML there is a single unified model that contains design features, manufacturing features, and the tool path.

4. Description of Effort and Accomplishments

4.1 3D Manufacturing Module (Chisels)

A 3D manufacturing module named *Chisels* incorporating many of the capabilities discussed above has been developed within AML. The module is capable of producing complete process plans for machining prismatic and non-prismatic parts. The module has a feature based design environment that facilitates the description of the part geometry, specifying relations between features, and defining geometric constraints. The 3D manufacturing module has a fully integrated process planner supporting the general requirement of manufacturing and inspection. Present manufacturing capabilities include milling and hole making process planning as well as cost estimation. A unique tool path planner for NC is fully integrated within AML.

The automated path planner supports **geometric reasoning** capabilities which are suitable for spot welding, arc welding, spray painting, water jet cutting, inspection, and other processes that require positioning and motion control of a tool/probe moving on or about complex shapes and surfaces. Capabilities to control multiple path offsets, distances from, and orientation between the tool and the surface are also automated. The uniqueness of the integrated and dynamic link between the geometrical modeler and the path planner is a result of the AML's single underlying object-oriented architecture.

4.1.1 Chisels User Interface

The following figures are used to illustrate the steps the user must follow to generate a process plan in *Chisels* :

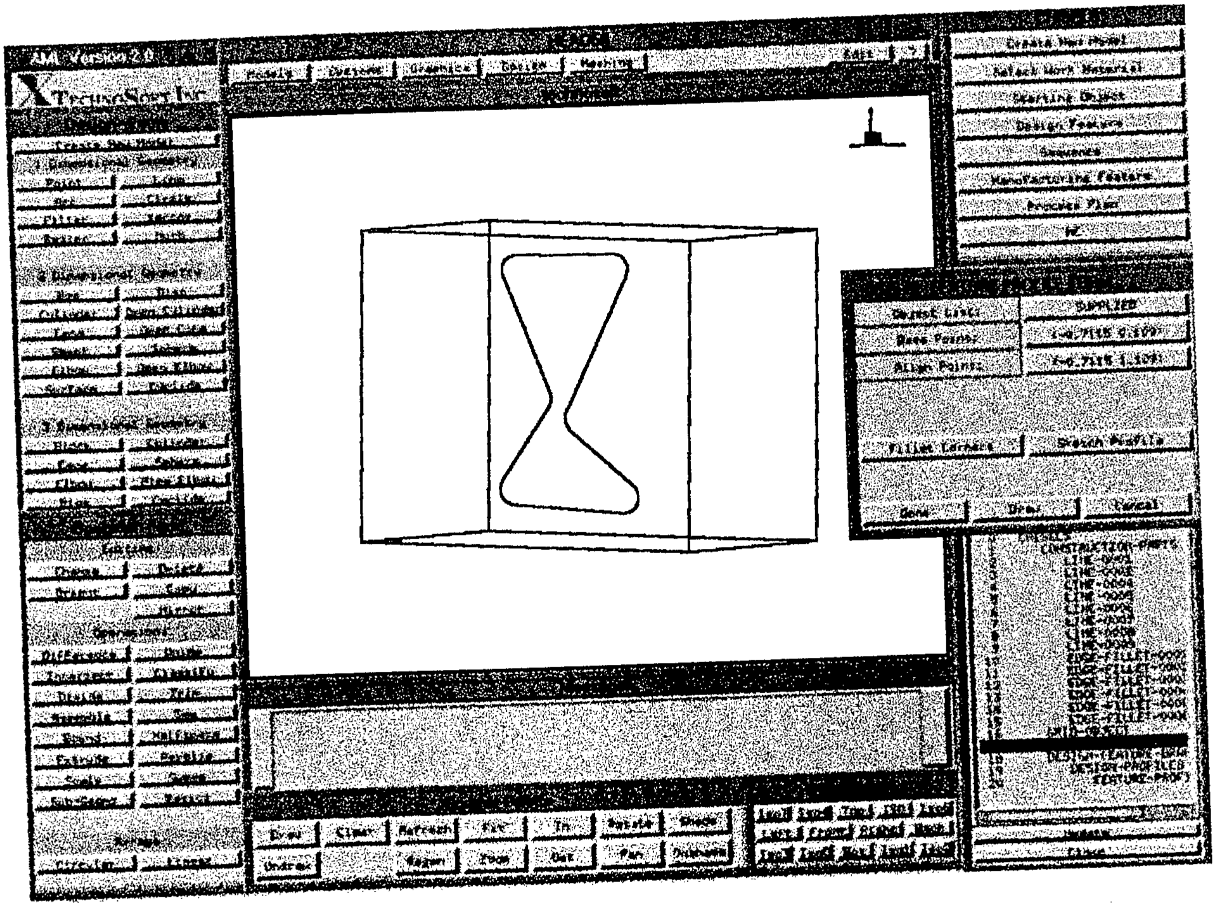
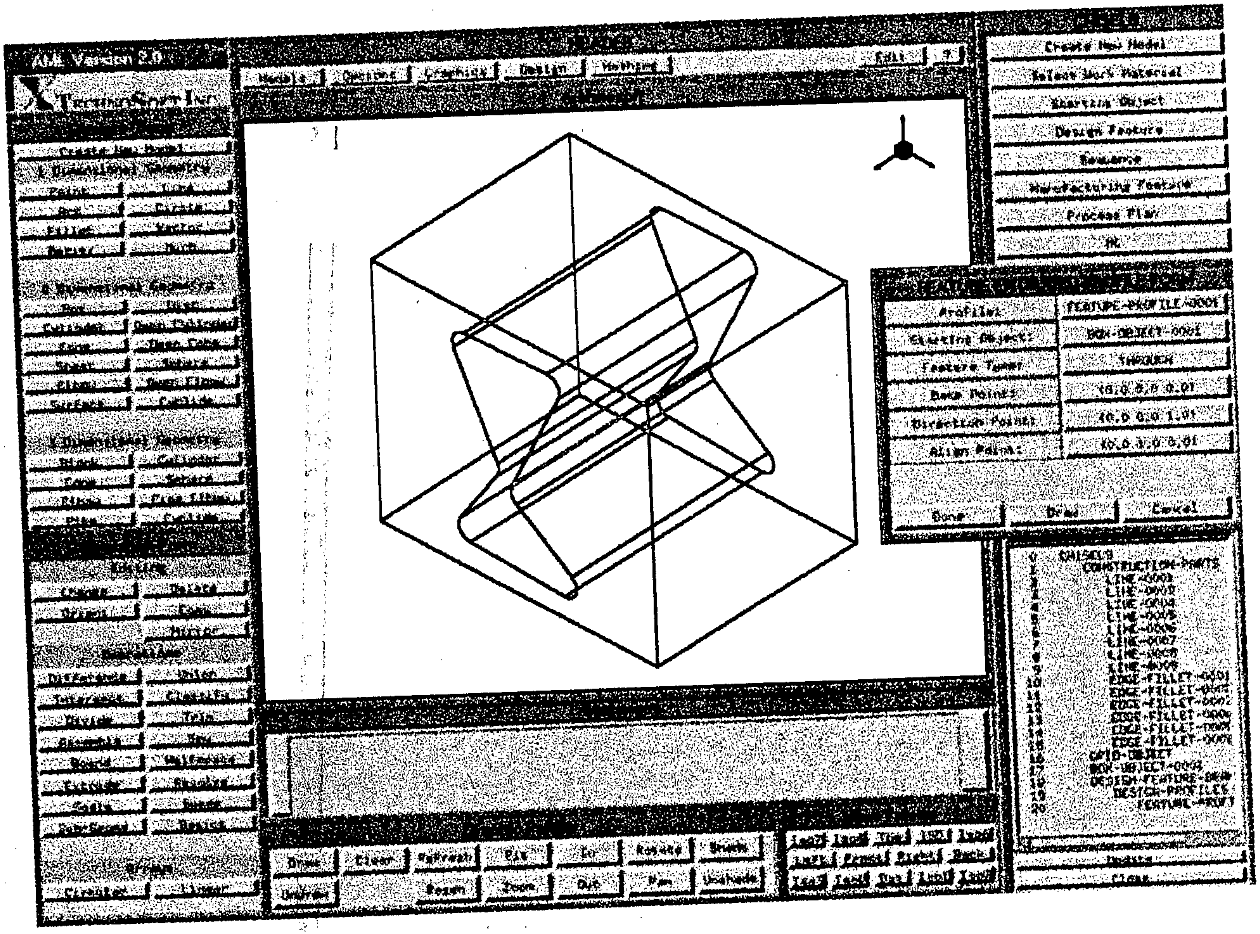


Figure 4-1. Sketching Example

In Figure 4-1 the user has sketched an hour-glass shaped profile. The user wishes to machine this profile out of prismatic shape. The user sketched the 2D profile using the free form profile sketcher. *Chisels* can handle incomplete design specifications, i.e., a number of features in a part may be for weight reduction only, therein they are not mated to other features and may be considered as non-critical. The designer may want to allow the system to specify the tolerances and fillet radii associated with the non-critical features. In the *feature profile form,* the designer may specify that a 2D feature is non-critical by drawing lines that make up the feature and then asking the system to determine the appropriate fillet radii that guarantees minimum machining time. The fillet radii are determined by taking into account the geometry of the profile and the tools available in the tool bin.



Profile: FEATURE-PROFILE-0001

Starting Object: BOX-OBJECT-0001

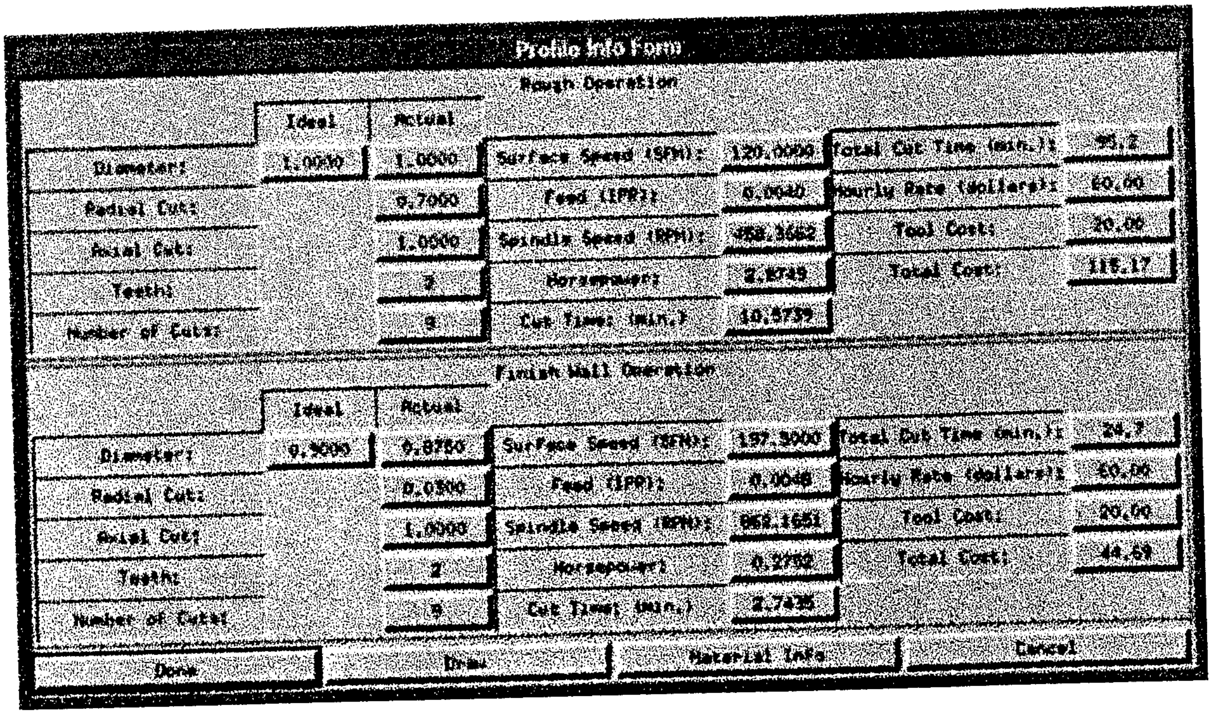
Feature Type: THROUGH

Figure 4-2. Extruded Profile Example

In Figure 4-2 the user extrudes the 2D profile along the z-axis, the result is a cavity that needs to be machined out. In this case, the user specifies that this cavity is a through cavity. By doing so, the dimension of the cavity along the extrusion axis requires changing the dimension of the starting block along the z-axis to encompass the depth of the cavity since the cavity is extruded along the z-axis. This association between the feature and the starting block is one aspect of creating a parametric associative model. The associative nature of AML is what facilitated the building of *Chisels*.

After defining the design feature(s) the user specifies the setups, and within each setup the order of machining the respective features. When specifying the order of machining the features the system automatically re-dimensions the features so as to reflect the order specified. After the features are re-dimensioned the user may now query the system for the process plan details associated with the cavity. The process plan generated is a complete process plan that contains:

- Operations needed to machine the feature (relief holes, roughing operations, etc.)
- A description of the tools needed to complete each operation
- Speeds, feeds, and horse power requirements
- Cost associated with completing each operation



Rough Operation

	Ideal	Actual
Diameter:	1.0000	1.0000
Radial Cut:		0.7000
Axial Cut:		1.0000
Teeth:		3
Number of Cuts:		9

Surface Speed (SFM):	120.0000
Feed (IPR):	0.0040
Spindle Speed (RPM):	458.3662
Horsepower:	2.8749
Cut Time: (min.)	10.5739

Total Cut Time (min.):	95.2
Hourly Rate (dollars):	60.00
Tool Cost:	20.00
Total Cost:	115.17

Finish Wall Operation

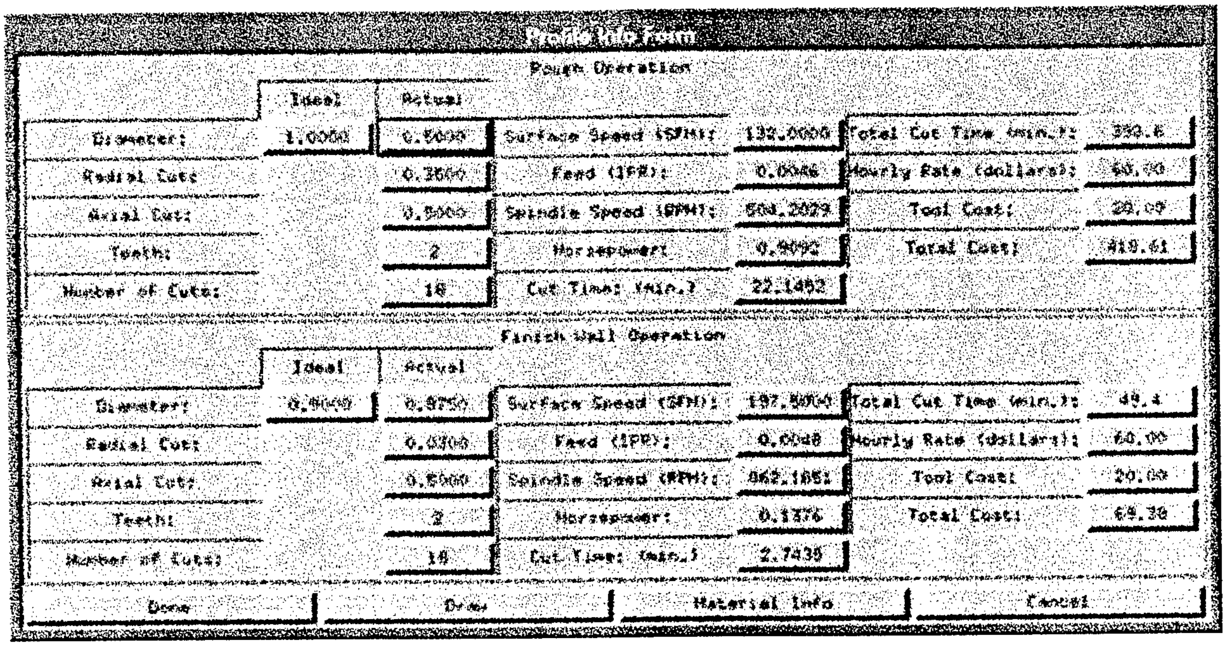
	Ideal	Actual
Diameter:	0.9000	0.8750
Radial Cut:		0.0300
Axial Cut:		1.0000
Teeth:		2
Number of Cuts:		9

Surface Speed (SFM):	197.3900
Feed (IPR):	0.0048
Spindle Speed (RPM):	862.1651
Horsepower:	0.2792
Cut Time: (min.)	2.7435

Total Cut Time (min.):	24.7
Hourly Rate (dollars):	60.00
Tool Cost:	20.00
Total Cost:	44.69

Figure 4-3. Using 1.0-Inch Tool for Roughing

The process information is displayed in a spread sheet like format as shown in Figure 4-3. The user may change the values stored in any of the cells. A change in one of the cells may affect some or all of the other cells. For example, a change in the roughing tool diameter affects the speeds, feeds, horse power requirements, and the cost associated with roughing the feature, this is illustrated in Figure 4-4. This tooling material, size and rate associativity is very helpful in investigating what-if scenarios.



Rough Operation

	Ideal	Actual				
Diameter:	1.0000	0.5000	Surface Speed (SFM):	132.0000	Total Cut Time (min.):	398.6
Radial Cut:		0.3600	Feed (IPR):	0.0046	Hourly Rate (dollars):	60.00
Axial Cut:		0.5000	Spindle Speed (RPM):	504.2029	Tool Cost:	20.00
Teeth:		2	Horsepower:	0.9092	Total Cost:	418.61
Number of Cuts:		18	Cut Time: (min.)	22.1492		

Finish Wall Operation

	Ideal	Actual				
Diameter:	0.9000	0.8750	Surface Speed (SFM):	197.5000	Total Cut Time (min.):	49.4
Radial Cut:		0.0300	Feed (IPR):	0.0048	Hourly Rate (dollars):	60.00
Axial Cut:		0.5000	Spindle Speed (RPM):	862.1651	Tool Cost:	20.00
Teeth:		2	Horsepower:	0.1376	Total Cost:	69.38
Number of Cuts:		18	Cut Time: (min.)	2.7439		

Figure 4-4. Using 0.5-Inch Tool for Roughing

To investigate using a smaller tool to machine a feature, the tool diameter value is changed and the machining parameters update their values to reflect the new tool diameter. In Figure 4-3 the cost associated with roughing the feature with a tool diameter of 1.00-inch is $115.17, compared with a 0.50-inch tool which raises the cost to $418.61 as shown in Figure 4-4.

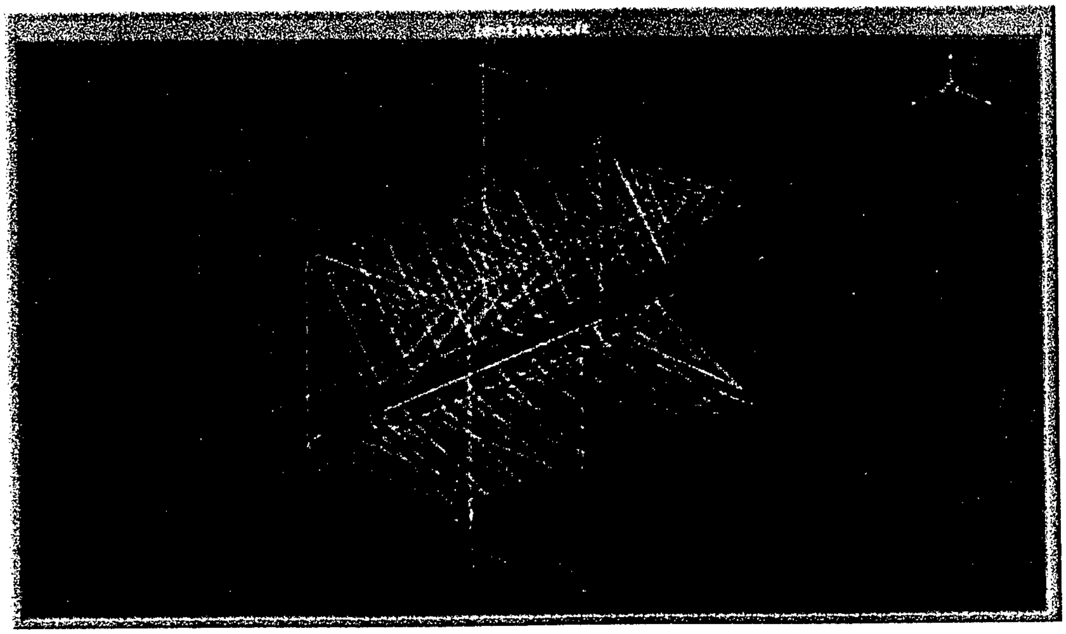


Figure 4-5. Tool Path Using 1.0-Inch Tool

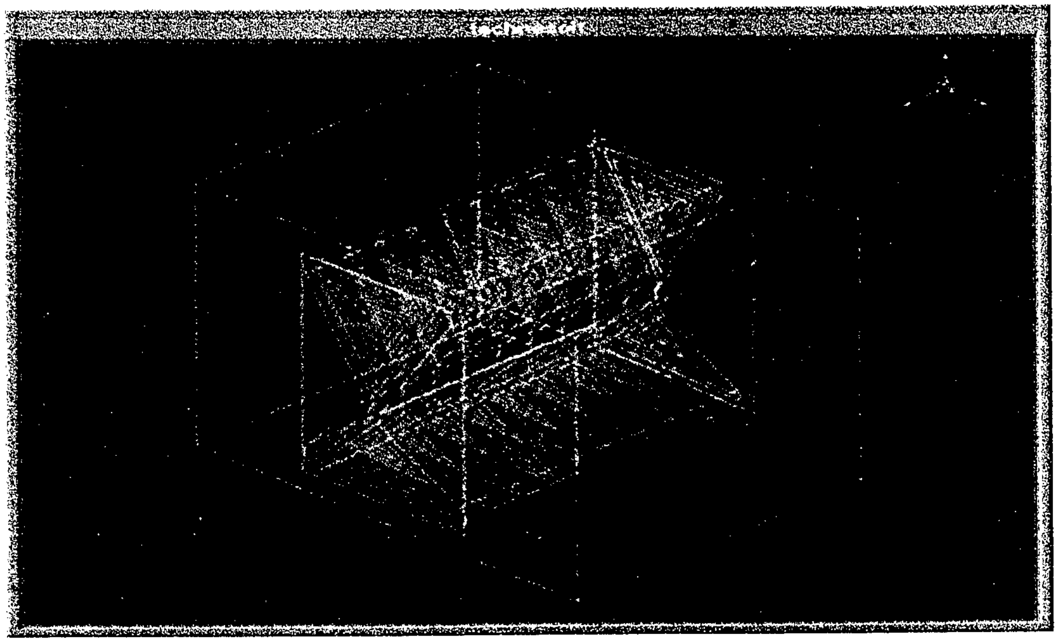


Figure 4-6. Tool Path Using 0.5-Inch Tool

The tool diameter affects the tool path generated, so as the user changes the tool diameter the tool path is automatically updated, this is illustrated in Figure 4-5 and Figure 4-6. Note in Figure 4-5, the roughing tool diameter is 1.00 inch, while in Figure 4-6 it is 0.5 inch.

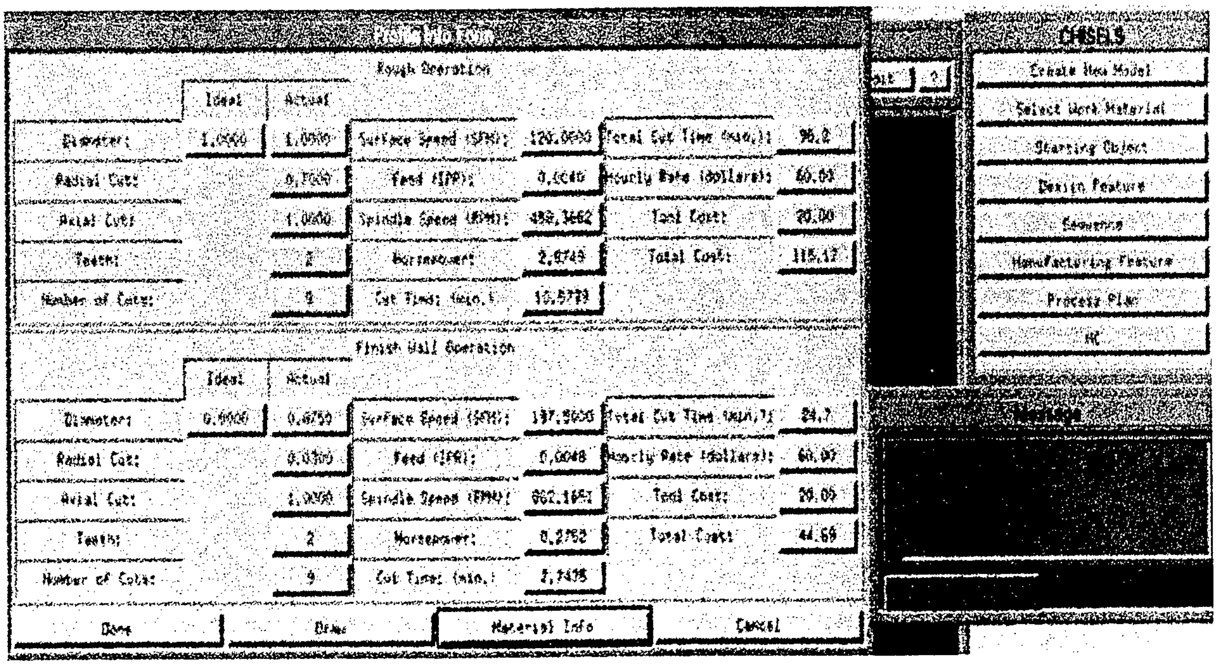
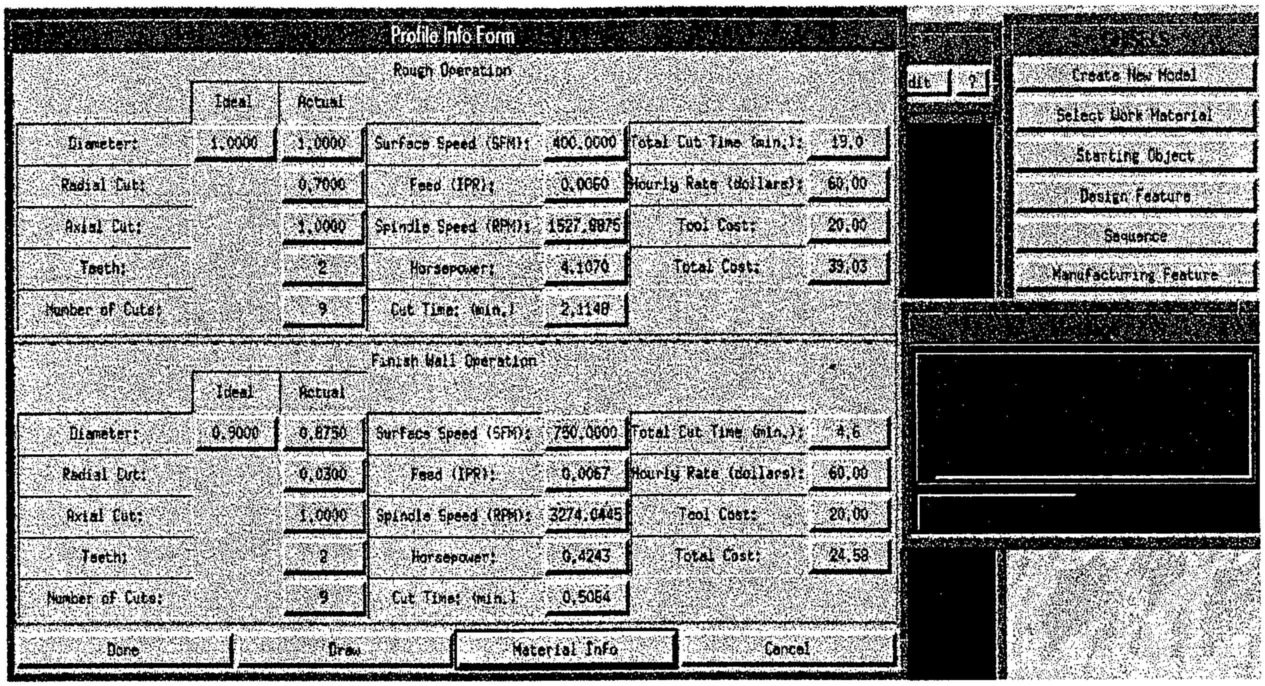


Figure 4-7. Cost When Using 1020 Carbon Steel



Profile Info Form

Rough Operation

	Ideal	Actual				
Diameter:	1.0000	1.0000	Surface Speed (SFM):	400.0000	Total Cut Time (min.):	19.0
Radial Cut:		0.7000	Feed (IPR):	0.0060	Hourly Rate (dollars):	60.00
Axial Cut:		1.0000	Spindle Speed (RPM):	1527.8875	Tool Cost:	20.00
Teeth:		2	Horsepower:	4.1070	Total Cost:	39.03
Number of Cuts:		9	Cut Time: (min.)	2.1148		

Finish Wall Operation

	Ideal	Actual				
Diameter:	0.9000	0.8750	Surface Speed (SFM):	750.0000	Total Cut Time (min.):	4.6
Radial Cut:		0.0300	Feed (IPR):	0.0067	Hourly Rate (dollars):	60.00
Axial Cut:		1.0000	Spindle Speed (RPM):	3274.0445	Tool Cost:	20.00
Teeth:		2	Horsepower:	0.4243	Total Cost:	24.58
Number of Cuts:		9	Cut Time: (min.)	0.5064		

Figure 4-8. Cost When Using 6061 Aluminum

The material information included in the model can also be changed to perform what-if scenarios. For example, in Figure 4-7 the cost associated with roughing a feature is $115.17 when the starting block is made of 1020 Carbon Steel, while the cost associated with roughing the same feature is only $39.03 when machined from 6061 Aluminum.

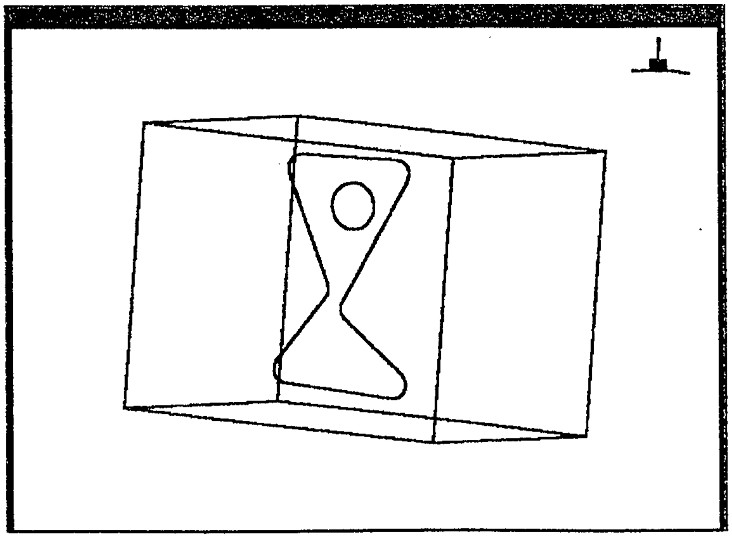


Figure 4-9. Updated 2D Profile

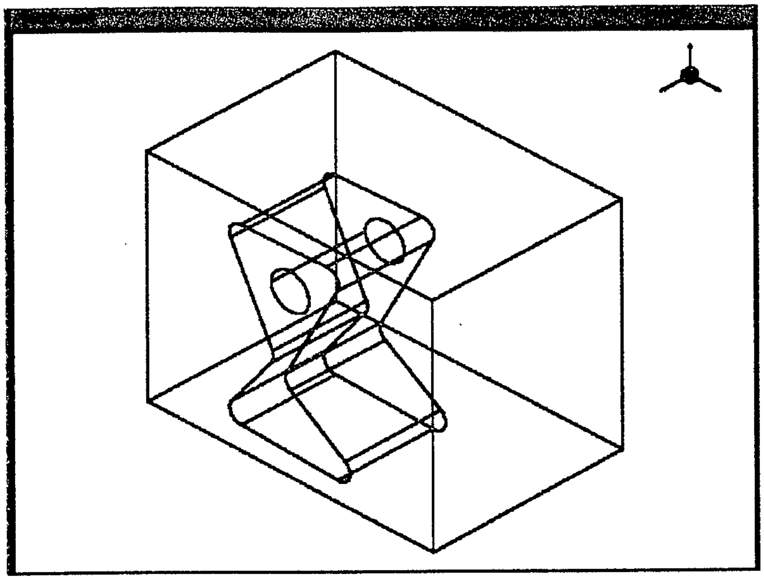


Figure 4-10. Updated 3D Feature

The user may wish to change the geometry that is being machined. For example, consider machining a blind cavity, and adding a boss to the feature. In a conventional CAD/CAM system, the whole part would need to be redesigned. In *Chisels* the user merely updates the 2D feature in Figure 4-9 by changing the feature from a through feature to a blind feature as in Figure 4-10.

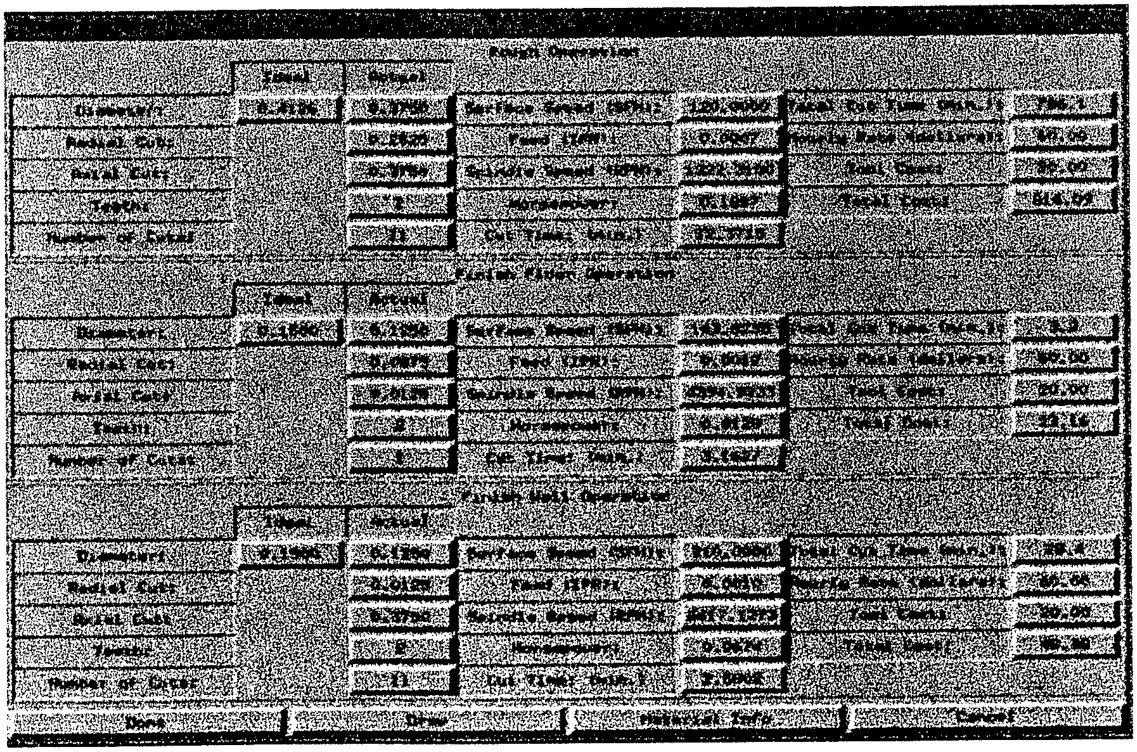


Figure 4-11. Process Plan for Updated 3D Feature

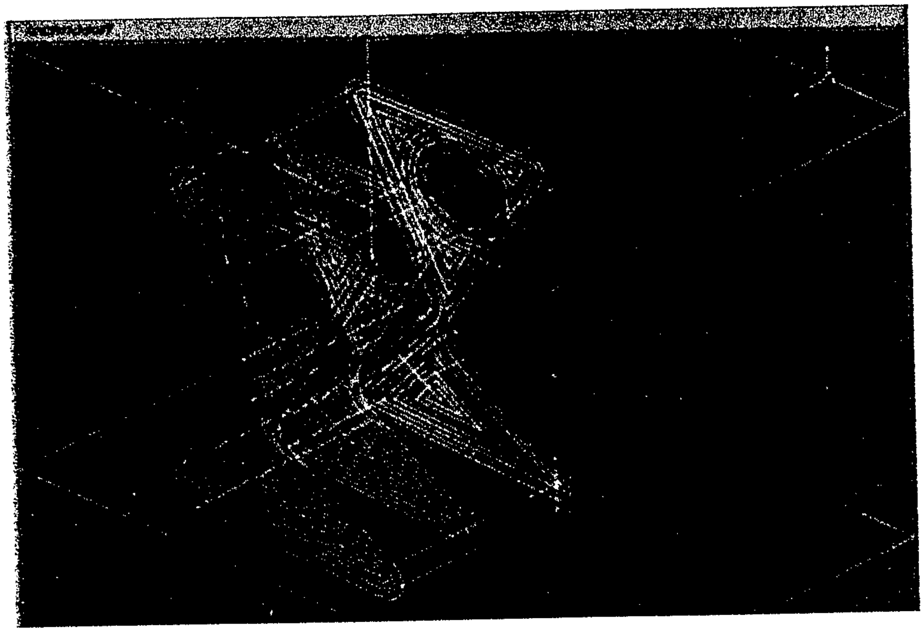


Figure 4-12. Updated Tool Path

These changes also affect the process plan, and tool path as is illustrated in Figure 4-11 and Figure 4-12 . Note, an extra, finish-floor operation is needed with a blind feature.

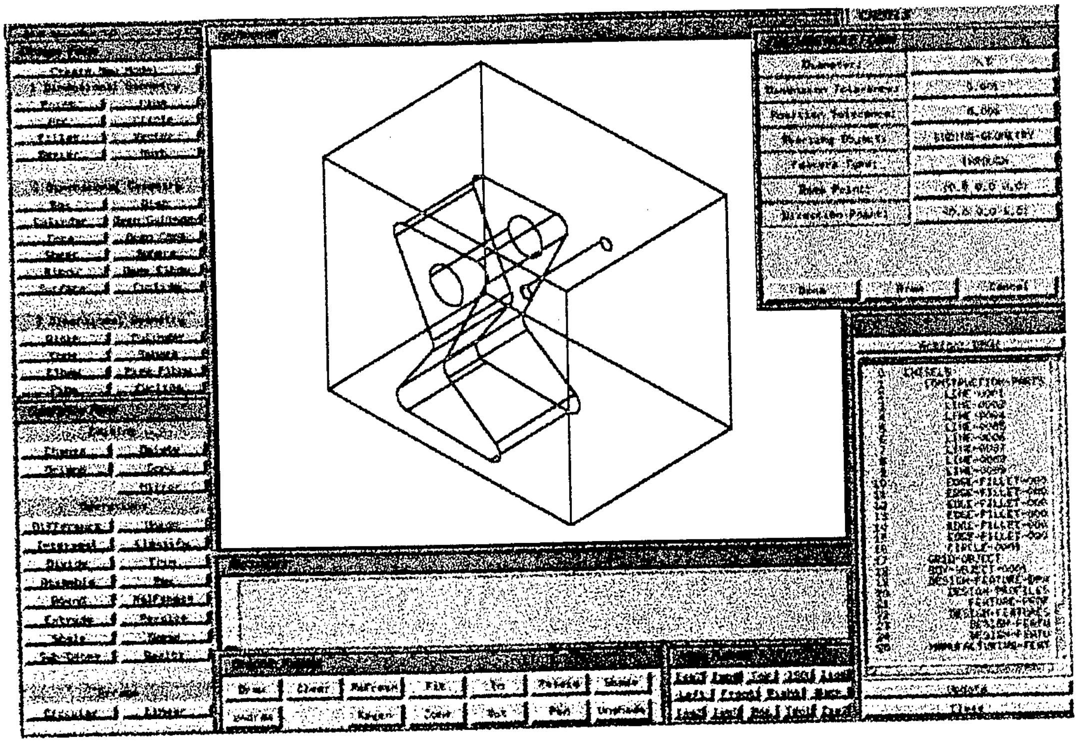


Figure 4-13. Adding a Single Diameter Hole

To add a single diameter hole to the part, a single diameter hole from the design menu is selected. In doing so the user has to specify the position, orientation, dimensions, and the tolerances associated with the hole feature using the form in Figure 4-13.

The user may query *Chisels* for the process plan associated with the feature by selecting the associated setup the feature is contained in, and identifying the feature sequence within the setup. As a consequence, *Chisels* will automatically re-dimension the feature to reflect the machining sequence. For a hole of radius of 0.5 inch, depth of 4.0 inch, positional tolerance of 0.001 inch, and a dimensional tolerance of 0.001 inch *Chisels* has recommended the following operations based on the tools available in the tool bin, and the tool specifications:

- center drill
- drill
- peripheral mill (to insure the positional tolerance, and obtain the appropriate hole size)
- ream (to insure the dimensional tolerance)

The above changes appear in the form depicted in Figure 4-14. To indicate that an operation is not needed the button associated with that operation is highlighted by a text color change.

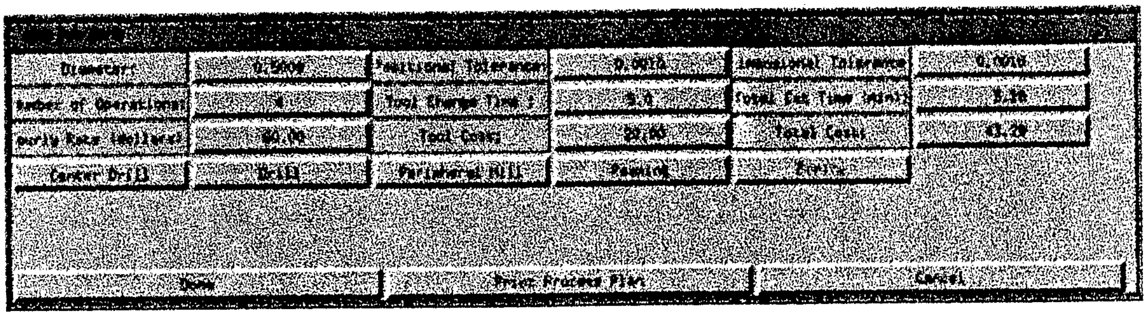


Figure 4-14. Single Diameter Hole Process Plan, <rad=0.5, pt=0.001, dt=0.001>

Changing the radius, depth, dimensional, and/or positional tolerances also affects the process plan associated with the hole. For example changing the dimensional tolerance from 0.001 to 0.008 means that the reaming operation is not needed any more, this is illustrated in Figure 4-15. The cost associated with machining the hole was $43.29 when the dimensional tolerance was 0.001, it went down to $37.64 when the dimensional tolerance was changed to 0.080.

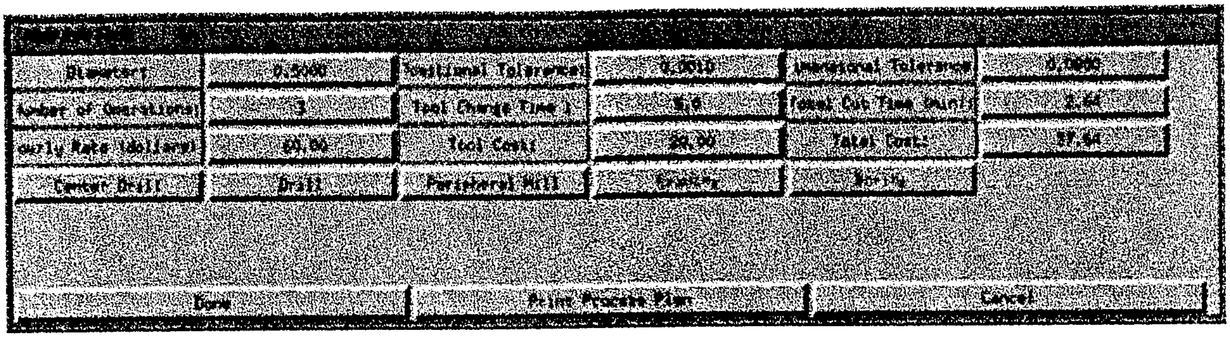


Figure 4-15. Single Diameter Hole Process Plan, <rad=0.5, pt=0.001, dt=0.008>

In Figure 4-16 the dimensional tolerance is 0.08 and the positional tolerance is 0.08, this means that the user needs only center drill and drill. Reaming and peripheral milling are not needed. The cost to machine the hole with the above tolerance is now $31.18.

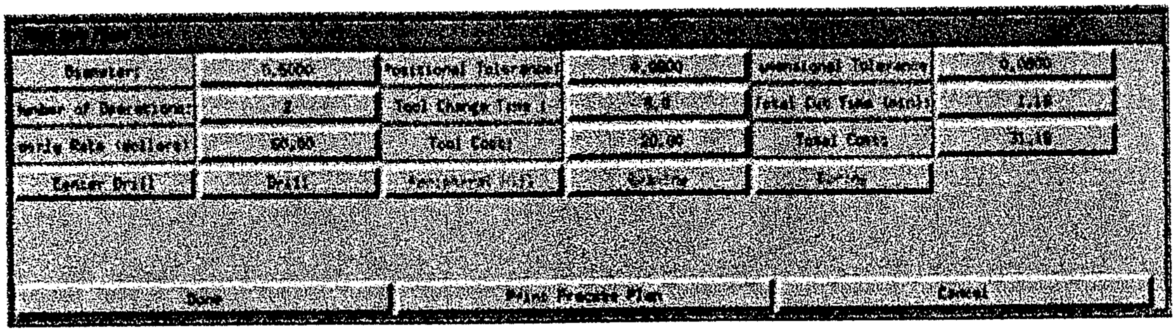


Figure 4-16. Single Diameter Hole Process Plan, <rad=0.5, pt=0.08, dt=0.08>

The system generates G code that can be used to run an NC machine (the generated code may need to be modified depending on the NC machine it needs to run on). In addition to that, the user can generate a version of the process plan that can be used on the shop floor (operation name, tool specification, speeds, feeds, and machining time are included in this version of the process plan).

4.1.2 Tooling and Machining Data

Tooling data is stored in ASCII files and these files can be easily edited. To add a tool to the tool bin all the user has to do is make a new entry in the tool data file with the new tool specifications. Machining knowledge is associated with the shape objects, i.e., an instantiated process object is associated with a design (shape) feature. The process plan produced depends on the feature type, dimension, and tolerances. The process plan can be customized to reflect the practices in the shop floor, this can be easily done by modify the processing objects.

4.1.3 Functionality

Chisels is meant to be used as a tool to bridge the gap between designers and machinists. A designer with little or no knowledge of machining can now design a part and examine what-if scenarios and observe the affects of changing the design. For example, the designer can change the fillet radii of a profile and observe what affect the change(s) have on the production cost. The produced cost is accurate, since the tools used are those available in the shop floor, and the process plan reflects the practices used on the shop floor. A machinist can get a model from the designer and produce a complete process plan, in the form of G code and/or a report.

4.2 Automated Mesh Generated for Finite Element Analysis

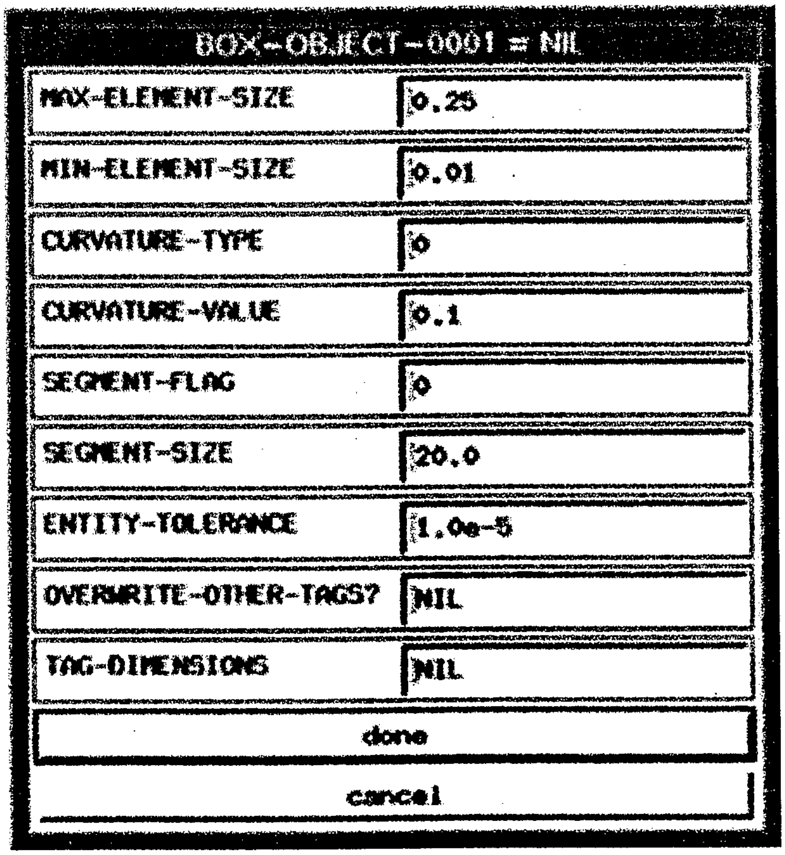
The Advanced Finite Element Modeling Module allows for tight integration of the mesh generation and analysis applications. This module enables the definition of an analysis problem by defining regions of interest, material models, solution strategies and other requirements for analyzing various problems utilizing a mesh generator and a Finite Element solver. The various entities of interest in the analysis model are modeled as AML classes that can be utilized to instantiate a complete Finite Element Analysis problem model. The problem can be associated with the geometric objects as well as the mesh.

AML presents a unique mechanism for enhancing the part geometry (AML Object) to mesh. The programmable tagging (**Attribute Tagging and Propagation**) of the vertices, edges and faces of geometry for selective refinement of the mesh, and automatic meshing the geometry is uniquely presented in a syntax consistent with the AML Object/Class definition. AML provides objects for meshing as well as a mesh user interface supporting a complete customizable pre-processor. It also provides methods and a user interface for visualizing the mesh by querying the mesh database created by the mesh generator.

The AML finite element modeling capabilities include an Automatic Mesh generator supporting 4 node "tet," 10 node "tet," "hex," and user defined h-P adaptive "tet" meshing. The meshing capabilities include the ability to control and easily modify the mesh attributes (including curvature based refinement) for any geometry. Meshing also supports mixed dimensional (0D, 1D, 2D, & 3D) non-manifold geometry in a single pass. Additional capabilities include building a solid/surface model from a mesh, that is used as an object in AML supported by all AML Booleans and other operations. This object could be re-meshed resulting in a complete different mesh with attributes different from the original mesh properties.

4.2.1 Attribute Tagging and Propagation

Attribute tagging and propagation are used for facilitating association of information between entities in a geometric model. This information needs to be conveyed to processing objects as well as meshing or analysis. In a parametric modeling environment, reconfiguring a model involves the modification of the parameters at the construction level and regeneration of the final geometric model. Hence any new information would need to be propagated to the final geometry and associated views each time the model is reconfigured. This could be a very tedious task requiring major interaction with the user and delays in the engineering cycle. First, using attribute tagging, the new information is associated with the construction geometry. Next, every associated operation, including final design, analysis, and processing have the tag information passed on through attribute tagging. AML is the only parametric modeling system that provides the capability to propagate attributes through geometric operations. Therein, AML automates the extraction of required data for finite element modeling and analysis processes. Figure 4-17 illustrates the attribute tagging form which can be easily customized by the user.



MAX-ELEMENT-SIZE	0.25
MIN-ELEMENT-SIZE	0.01
CURVATURE-TYPE	0
CURVATURE-VALUE	0.1
SEGMENT-FLAG	0
SEGMENT-SIZE	20.0
ENTITY-TOLERANCE	1.0e-5
OVERWRITE-OTHER-TAGS?	NIL
TAG-DIMENSIONS	NIL

Figure 4-17. Attribute Tagging Interface

4.2.2 Mesh Generation

Automatic Mesh Generation is a module that allows for the tight integration of the geometry, various mesh generation and analysis applications. AML enables the selection of the geometry to mesh, tags the respective vertices, edges and faces of geometry, and allows for the mesh to be refined selectively. Figure 4-18 illustrates the mesh interface, and a meshed object; this interface can also be customized by the user.

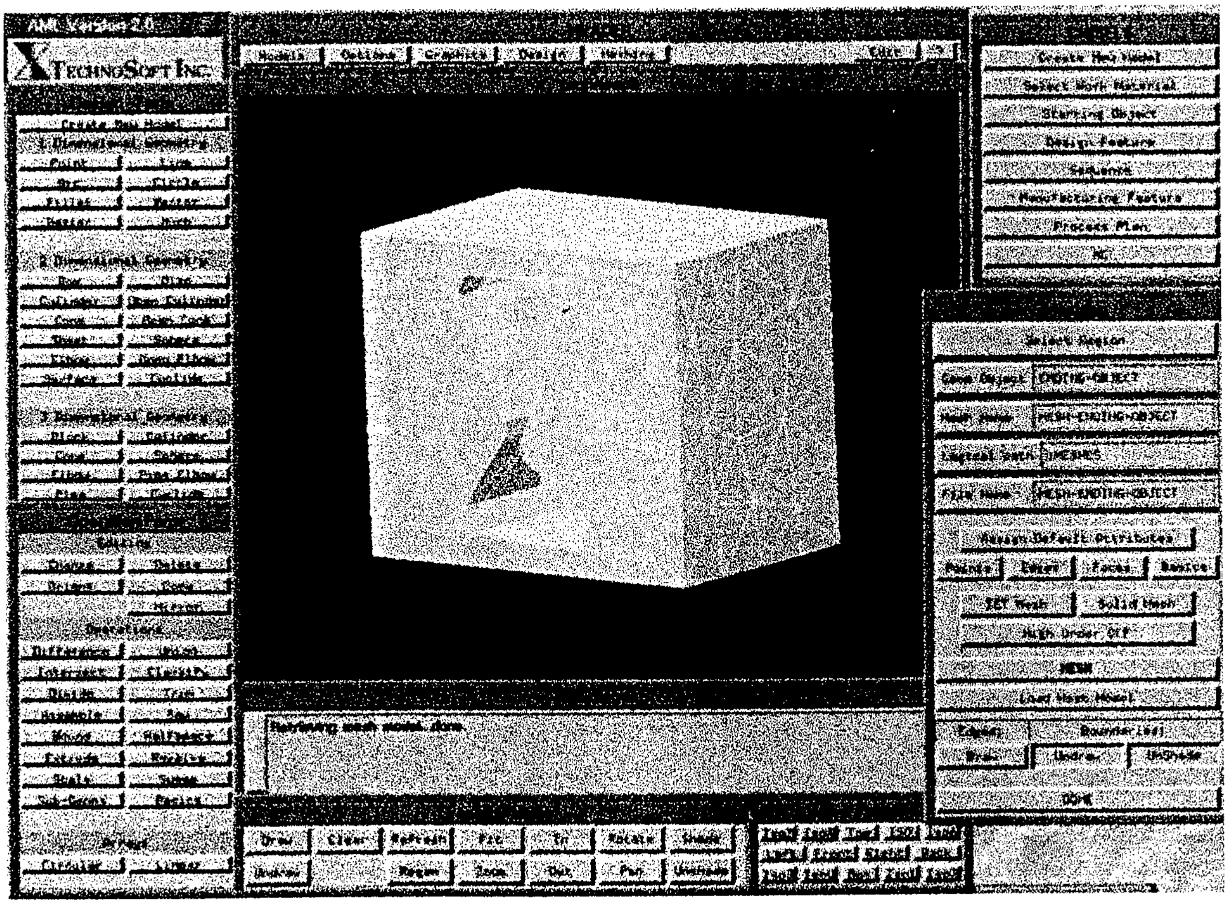


Figure 4-18. Mesh Interface, Meshed Object

4.2.3 Finite Element Analysis

The finite element analysis interface system is a geometry-based system. The finite element analysis objects can be associated with any object in the part model. Approximately two-thirds of the time needed for finite element model building is reduced, since errors in geometry model building are eliminated. The FEA system can be used to drive a number of different solvers. The system will also enable the analysis problem to be defined by selecting regions of interest, material models, solution strategies and other requirements for analysis such as mesh generation.

4.3 Inspection Planning

To generate an inspection plan for inspecting a part is a tedious and time-consuming process, it can take an engineer up to a year to produce the scan plans to inspect a part. The scan plans produced are very rigid, it is very difficult for users to make minor changes to existing scan plan specifications (e.g. dimensions, tolerances), and inspection criteria. Automation of the inspection planning (scan plan generation) will offer the ability to respond more quickly to changes to the inspection requirements. It would also allow the user to develop/acquire scan plans for new parts more quickly. The inspection planning process is a constraint, geometry-driven process. Because of the flexible, parametric nature of AML and the geometric reasoning capabilities available, AML is a natural platform for developing an inspection planning system.

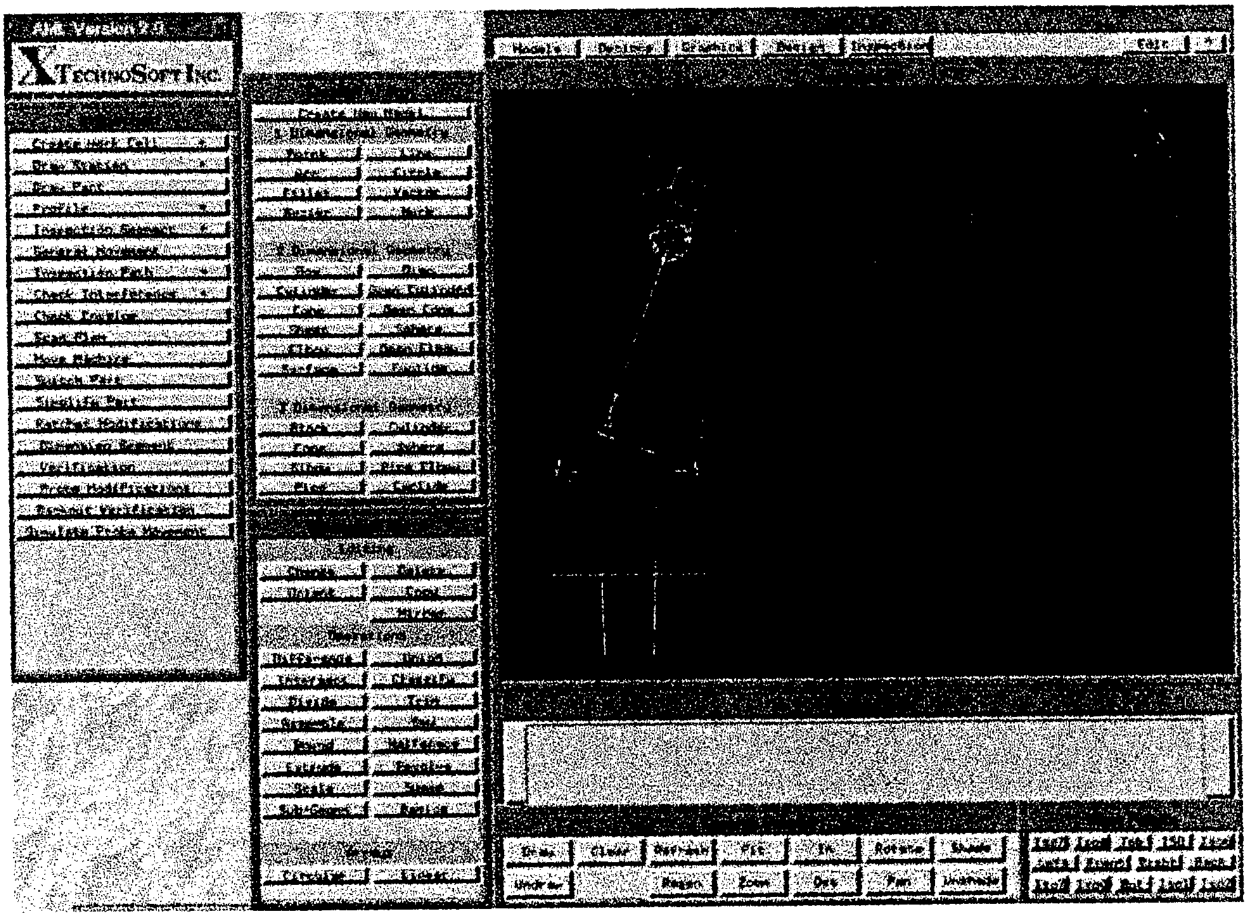


Figure 4-19. Overall Look of the Inspection Planning Module

The inspection planning module is capable of reading an electronic part definition, semi-automatic generation of a probe path, collision detection, and complete scan code generation for revolved geometries.

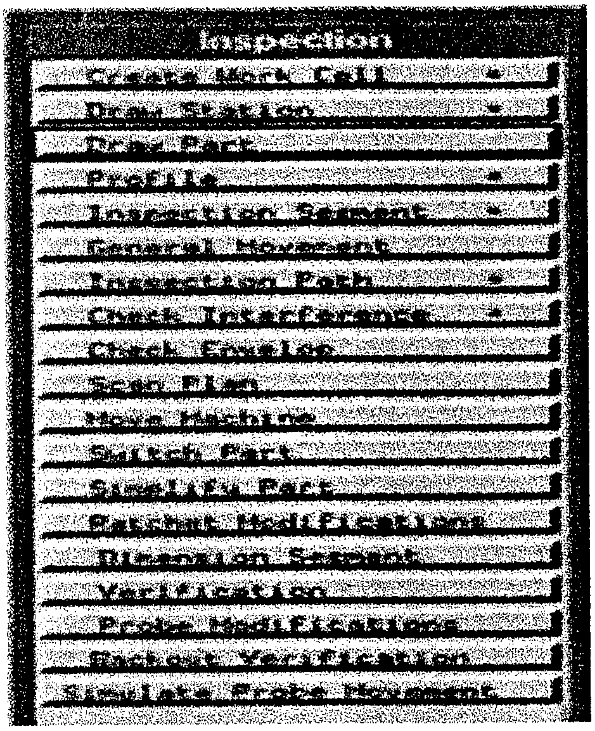


Figure 4-20. Inspection Menu

Figure 4-20 illustrates the inspection menu. The users of the system can generate scan plans using the inspection module. The users of the system are provided with some control over the way the process plan is generated.

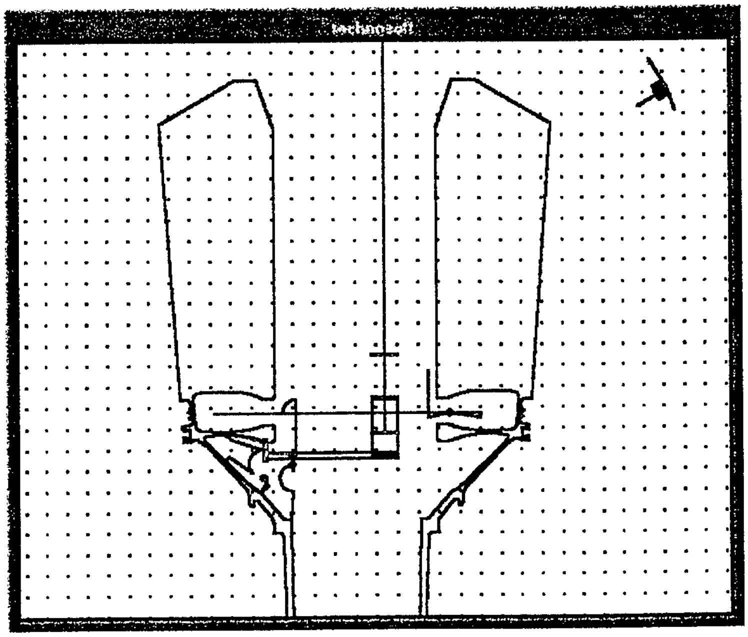


Figure 4-21. Probe Going Through Inspection Path

Figure 4-21 illustrates the probe going through an inspection path. A probe database is maintained, this will allow the users to define new probes which can be used to inspect new parts.

5. Results Summary

The results of this small business innovation research effort was the development of three integrated product-process design modules:

- machining
- inspection
- meshing and FEA modules

The unified part model methodology was fundamental to the tight integration of these modules with the design environment, As implemented, this means that a user can design a part for machining and/or inspection, and then perform meshing and finite element analysis on the part. At this stage the inspection module can only deal with revolved parts. These and subsequent modules will help in reducing the cost of design, processing, and analysis as the gap between engineering disciplines is bridged with a unified part model methodology.

6. Conclusions

In this report a review of the issues related to the integration of product and process design have been presented. The research issues have been discussed and an implemented solution presented. Previous systems have been designed to take input either from a group technology code or from a user-created descriptive file. In some instances, a descriptive language has been implemented using features to interpret the part geometry, and convert it into a special format for system input.

In the past ten years, we have seen tremendous growth in the development of CAD systems, which has led to an awareness of the growing gap between design and process planning automation. The system, AML, described herein is an attempt to bridge the gap between engineering disciplines. AML is unique in many aspects, but its unified part model and parametric nature are fundamental to the success of this effort.

We believe that, to date, AML is the only system capable of automatic process plan generation for machining and inspection. The system can be customized to reflect varying shop floor practices by modifying the processing objects.

A number of US corporations and partners in technology have already funded the technology transfer of the developed framework and methodology for integration within the AML. Initial AML releases incorporating such technology have received excellent reviews and major corporations have already committed to the use of the technology in their process automation programs.