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Critics and Advisors: Heuristic Knowledge and Manufacturability

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Abstract

In recent years, much of the progress in Computer-Aided Manufacturing has emphasized the use of simulation, finite-element analysis, and other science-based techniques to plan and evaluate manufacturing processes. These approaches are all based on the idea that we can build sufficiently faithful models of complex manufacturing processes such as machining, welding, and casting. Although there has been considerable progress in this area, it continues to suffer from difficulties: the first of these is that the kind of highly accurate models that this approach requires may take many person months to construct, and the second is the large amount of computing resources needed to run these simulations.

Two design advisors, *Near Net-Shape Advisor* and *Design for Machinability Advisor*, are being developed to explore the role of heuristic, knowledge-based systems for manufacturing processes, both as an alternative to more analytical techniques, and also in support of these techniques. Currently the advisors are both in the prototype stage. All indications lead to the conclusion that the advisors will be successful and lay the groundwork for additional systems such as these in the future.

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Introduction: A Hybrid model of Design

Artificial intelligence research views design, whether of a computer program, logic circuit or mechanical device, as a process of searching through a *design space* for solutions that satisfy such constraints as functionality, reliability, size, choice of material, etc. For physical devices, many of these constraints reflect the desire to minimize the cost and difficulty of making the component through a given manufacturing process. However, the addition of manufacturability constraints to the design space model raise significant theoretical and practical issues. Included are the issues as they apply to the development of computer programs that will assist human designers in improving the manufacturability of their designs.

Theoretical and practical issues are discussed in the context of two design advisors currently being built. *Near Net-shape Advisor,* helps a designer select the process (casting or rough machining) for bringing a part to the point that it is ready for finish machining. *Design for Machinability Advisor*, checks a part design for features, such as excessively tight tolerances, that make it difficult to machine. These programs are intended as design assistants: they will provide their users with information about options and potential problems, while leaving final decisions to the user. Correctness, usefulness and user acceptance of these programs depends on an appropriate understanding of the way that humans think and act during the design process. To improve our understanding of human design methods, the next section describes the design space model.

Models of Design

A central problem concerns the representation of the design space and the ways a human or machine moves through it to solve a design problem. *Top-down* approaches (figure 1) emphasize a hierarchical representation of design space: beginning with an abstract specification of a design problem, design proceeds through a series of specializations that ultimately produce a concrete artifact design. Generally, top-down approaches emphasize functionality in the initial specification, adding manufacturability constraints as design decisions are made.

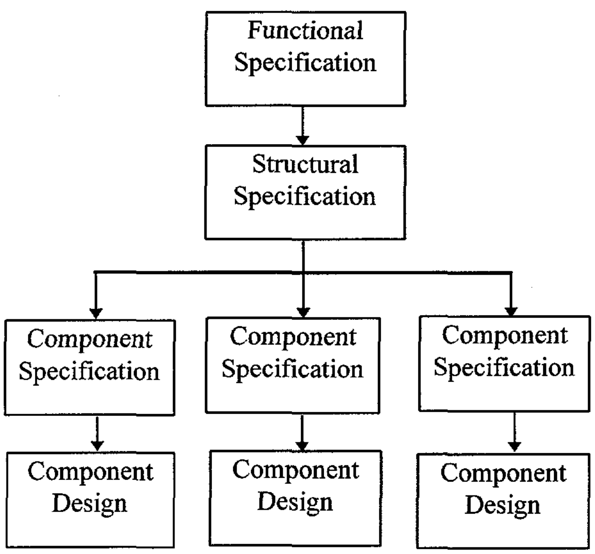

Figure 1

Construction of the manufacturablity advisors reveals a number of problems with the top-down model. For example, choice of a near net process can place strong constraints on the physical structure of an artifact: Cast parts tend to be difficult to weld due to the tendency of castings to form pores and other microscopic imperfections in the metal's crystalline structure. However, because casting can produce parts of greater complexity than machining, it also tends to promote "one-piece" designs that minimize the need for joining. These considerations suggest that near net process selection must take place early in the process when the artifact's basic structure is being determined. However, other factors that influence near net process selection cannot be known until much later in design. For example, thin walls are difficult to cast; accurate specification of wall thickness generally cannot be made until the design is fairly well advanced. As a result, it is difficult to locate this decision in the top-down model: Do designers choose a near net process early and adapt subsequent design decisions to fit that process? Or, do they postpone the decision until later, choosing a near net process that can best realize a design that was chosen for other reasons? It is clear that both approaches can lead to a less than optimal design/process combination.

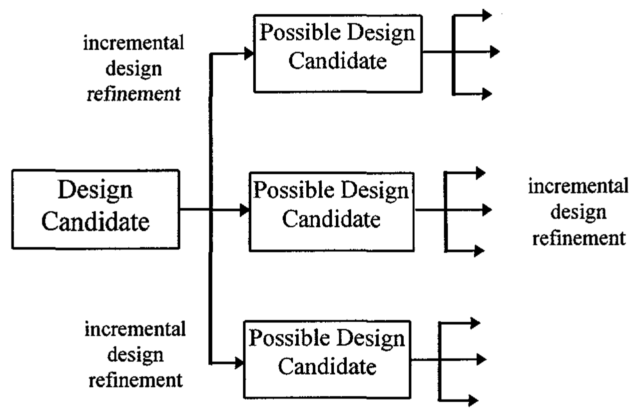

Figure 2

Incremental models, also known as *bottom-up* approaches, are an alternative that, like top-down models, have both positive and negative aspects. Incremental theories propose that designers work by constructing a complete solution to a simplified portion of the design problem. They then extend the functionality of this partial design incrementally, until it satisfies the full requirement (figure 2). Incremental design differs from top-down approaches in that all design refinements take place at the same level of abstraction. It can be characterized as a process of tinkering with candidate designs in an effort to improve their performance. Incremental models allow both functional and manufacturability constraints to be flexibly applied throughout the design process. However, practical experience indicates difficulties with this approach. Some difficult to machine features can be fixed through local, incremental changes: the designer can relax a tolerance, or change a fillet radius without requiring major changes in a design. However, other problems require extensive re-design. For example, excessively deep holes may be difficult to machine accurately. One solution that a designer should consider is to re-design the part to eliminate the such holes entirely. The incremental model is limited in its ability to account for this sort of large jump through the design space. For similar reasons, the incremental model cannot provide a suitable answer to the problem of near net process selection.

These observations suggest a hybrid model of design that exploits both hierarchical decomposition of the design problem and the ability to move incrementally through design space. *Opportunistic design* recognizes the importance of hierarchical representation of the design space [Guindon, 1990]. However, it also recognizes that humans navigate this space in very flexible ways, moving freely between different levels of abstraction, using top-down design to capture major design features and incremental approaches to refine and evaluate those decisions. Humans are very good at deciding when to abandon an approach and move back to a higher level of abstraction to rethink decisions made at that level.

Opportunistic design approaches encompass many aspects of current design process, including the problems outlined in this discussion. For example, near net process selection can work initially at a high level of abstraction, choosing a basic process/shape combination that considers the costs of joining and assembly. If subsequent refinements to this design create features that are difficult to produce with the chosen process, the designer may either choose to modify the design to suit the process or retreat to an earlier stage of design and propose a new process/shape combination. Similarly, on finding a difficult to machine feature in a part, a human designer will distinguish problems that can be resolved with local, incremental changes from those requiring a more basic rethinking of the design. Again, this requires the ability to move freely through the design space, in a flexible manner that fits the opportunistic model.

Writing Advisors to Support Opportunistic Design

Adoption of the opportunistic model has several ramifications for the creation of design assistants. In particular, our work on design advisors has been shaped by the following implications of the opportunistic design model:

1. *Support different levels of abstraction by a design assistant.* Although our advisors are intended to infer relevant features from a CAD solid model, we must also recognize that much of their knowledge also needs to be available to the user early in design, when sufficiently detailed models may not be available. Consequently, we are providing the users with multiple representations of relevant knowledge: The advisors will use rules and methods to automatically search solid models for relevant features and analyze their effect on manufacturability. In addition, we will offer this knowledge to the users in the form of hypertext documents that will allow them to access it directly in the early stages of design.
2. *Reliance on heuristics to navigate design space.* Opportunistic design often requires the user to make decisions based on inadequate knowledge. For example, early selection of a near net process may require a decision before the ramifications of that process on the final design are well understood. Much of the knowledge used in this process is necessarily heuristic in nature. The advisors will need to function well in the absence of complete knowledge, either by making reasonable default assumptions about missing data, using fuzzy or probabilistic reasoning techniques, or exploiting appropriate heuristics to reason with partial information.

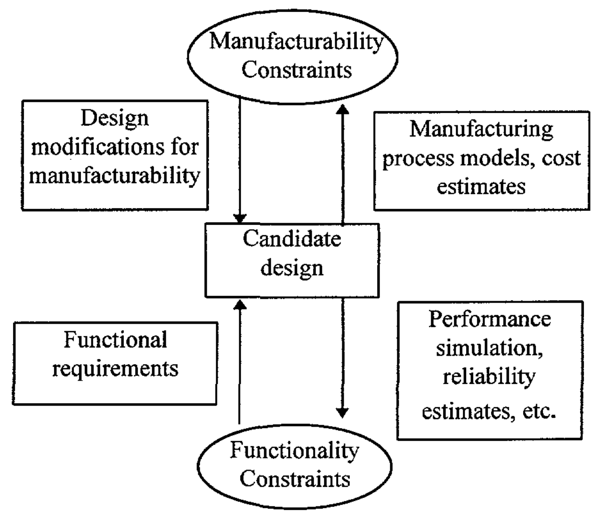

Figure 3

3. *Support for multiple views and representations of the design.* The strength of opportunistic design results from human's ability to combine easily multiple points of view in refining the design; this is difficult to capture in an artificially intelligent program, given the current state of the art. For example, analysis of the manufacturability of a feature requires a different representation of that feature than does an analysis of its functionality. We have approached this problem by recognizing that our advisors are specialists; they are intended to be part of a much larger design environment called the Product Realization Environment. This environment will incorporate tools for analyzing different aspects of design including

both functionality and manufacturability. These advisors, as well as future manufacturability advisors, will ignore functionality while other tools will emphasize functionality over manufacturability (figure 3). This approach will rely on the human user to select the appropriate tool for the current stage of design and integrate the findings of the different tools.

The remainder of this paper will present the advisors in more detail and discuss the specific ways in which they address these issues.

Near Net-Shape Advisor

Although most of the components being built here at Sandia National Laboratories and by industry require extensive finish machining, it is not always obvious that the part should be machined to a rough shape from stock metal. This decision is made early during the design phase and affects the manufacturing costs and schedule. Because of the design engineer's lack of understanding of manufacturing procedures and constraints, costs can be excessive when manufacturing the component per the design. Early in the design phase, the *Near Net-Shape Advisor* will assist the design engineer with design trade-off decisions for casting versus machining as the near net-shape manufacturing process. With the aid of the *Near Net-Shape Advisor*, the design engineer will invest more time during the conceptual phase of the design identifying machining and casting details.

The advisor will consider such factors as the estimated cost of different manufacturing processes, the availability of materials that meet the product requirements (strength, ductility, and conductivity) and the quantity of the component to be produced. A hypothesis for a component is created based on the part design, the material, and the manufacturing process by the advisor. Various assumptions will be generated through a selection of equivalent materials that will meet the product requirements input by the user. These are evaluated by the *Near Net-Shape Advisor*. Straightforward criteria exist for an assumption which definitely matches a machining or casting manufacturing process, however most of the hypotheses do not fit into either of these categories. Each hypothesis will be evaluated to suggest the most economical process for achieving near net-shape.

A matrix is being generated with 3 indexes of performance: cost, performance, and schedule. Models of this information are available in literature [Dallas 1976] and through trade associations. Casting and machining experts at Sandia are providing other supporting domain knowledge. From this matrix, a complex weighted sum equation will be created with the user selecting the important indices. Generally, performance is the key index. Each of the hypotheses will be evaluated by applying the weighted sum equation. Establishing the cost of a component, based on complexity and delta volume, is very difficult. Complexity of a component is determined by its features. In the literature, a common definition of feature is a set of adjacent faces bounding a depression. Such a definition is adequate for machining applications where the most common features are depressions caused by material removal (holes, pockets, and slots). It is inadequate for applications where other kinds of features (symmetries and orthogonal directions) are important. Features are defined as physical design characteristics and geometric patterns in a part [Ames 1988]. These features are considered manufacturing features which are recurring shapes with some fixed engineering significance. A feature is a parametric shape associated with such attributes as its intrinsic geometric parameters (length, width, depth, position, orientation, geometric tolerances, material properties, and references to other features) [Mantyla, Nau, & Shah, 1996]. Ames's work on feature recognition will be extended and accessed by the *Near Net-Shape Advisor*. The feature recognizer will identify whether the component can be machined from standard stock. Geometric features such as pockets, slots, and undercuts are identified by the recognizer. These features are indicators as to the complexity of the component and the identification of them will be necessary to recommend a near net-shape process.

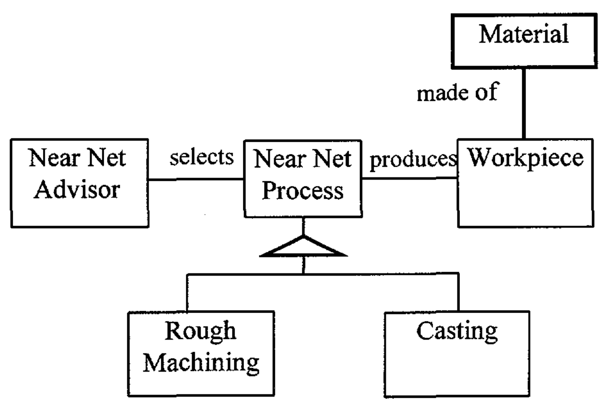

Figure 4

Near Net-Shape Advisor knowledge base has an object oriented architecture (figure 4). The near net advisor class will link to an instance of a near net-shape process and provide methods for querying the feature knowledge base. This knowledge base provides the interface to the feature recognition software to find instances of a feature as well as querying the user for additional information about the feature such as dimensions and tolerances. Rough machining and casting subclasses exist of the near net-shape process class. This set of subclasses can be expanded to accommodate other near net-shape processes. Each of these subclasses have their own set of rules which incorporate the weighted sum equation for estimating the suitability of manufacturing process. A score is given to each of the hypotheses. This assessment is shown to the user. An explanation of each assessment is available for the user which will list the advantages and disadvantages of each rough shape process.

Design for Machinability Advisor

A "spell checker" for product designs is the best description of the *Design for Machinability Advisor*. Much of the work in evaluating the machinability of designs focuses on such issues as the evaluation of tool paths to determine if all machined areas can be reached. There are, however, many other potential problems in a design that can complicate manufacturing, often unnecessarily. The advisor will bring manufacturing technology and knowledge closer to the process of component design. Cost and scheduling of the machining of a component are related to the number of setups required and the specialty of the manufacturing tools. To help the design engineer control both the costs and time of producing a component, the *Design for Machinability Advisor* will identify manufacturing features which require special tooling and increase setup and machining time. Impact of certain features is often not known by the engineer and the advisor will suggest to the engineer design trade-offs to reduce manufacturing time and cost. For example, many designers will specify hole sizes that do not correspond to standard drill bit sizes. It will be simple for the design advisor to detect such holes and suggest that they be changed to a standard size if the specialty size is not required. Many other common machining problems are a result of excessive tolerancing of the component. Often these tolerances are not a requirement for functionality of the component. By examining tolerances and looking for situations where they are unnecessarily tight or extremely difficult to achieve, the *Design for Machinability Advisor* can suggest to the design engineer design changes to eliminate multiple machining operations. Such factors as geometry, materials, and functionality are considered by the advisor when evaluating parts.

Geometry of a component is described as a set of features. Features are application specific. Machining is concerned with the volumes of material that must be removed to create the part from stock and with finding a means of accessing material removal regions with a tool. In contrast, castability analysis is concerned with features such as wall thickness and the flow of material within the boundaries when casting [Ames, 1991]. The *Design for Machinability Advisor* will also access the feature recognizer referred to previously, although the features that it identifies will be different. First, the feature recognizer will classify the component as a rotational part, sheet metal part, extrusion, or prismatic part. These classifications are based on shape defining features such as outer and inner diameters, sheets, bends, and extrusion sides. Based on this information, the recognizer will determine if the component will be machined on a lathe or mill, extruded, or formed from sheet metal. Second, the recognizer will then recognize shape modifying features (profiled holes, holes, slots, curved faces, and flats). This information will be incorporated by the *Design for Machinability Advisor* to perform an analysis of the design.

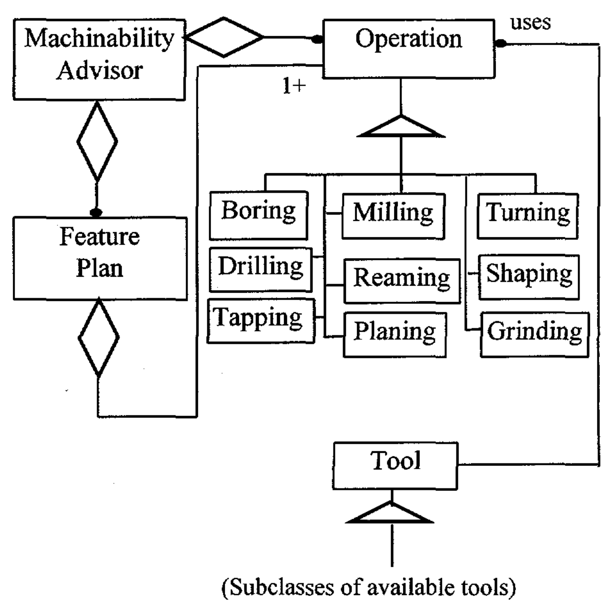

Figure 5

An object oriented architecture also exists for the *Design for Machinability Advisor* (figure 5). Modularity is a key factor of the advisor. Each set of rules associated with a features attribute is a module. A control structure applies rules for each feature attribute in turn. The machinability advisor class provides methods for querying the feature knowledge base for component features, the *Near Net-Shape Advisor* for information, and the user for functionality and material requirements. Rules for detecting feature interaction problems and excessive numbers of operations or tool changes are included in the machinability advisor class. This class provides access to the operation and feature plan classes. Operation applies rules for detecting problems in applying an operation to a feature. It has a set of subclasses, which are machining operations, which can be expanded. Operation links to an instance of tool, which determines the availability and cost of a tool, wear, breakage, and suitability for material. Methods for determining plausible sequences of operations for a feature and rules for detecting undesirable interactions between feature operations are in the feature plan class. As various rules are fired, feedback is provide to the user when problems occur with a machining operation. Suggestions are made to the user and a detailed discussion of the problem is available for the user.

Current Status and the Future

Currently both of the advisors are in the prototype stage. By the end of September the advisors shall be fully functional and provide the foundation for the development of complete systems. The investment of time in using both of these advisors will pay-off during the detail design phase and during manufacturing with a reduction in re-design cost because the machining versus casting decision was correct and the manufacturing features are more easily predicable. Design of the advisors has supported the needs of opportunistic design in a number of ways.

Although being developed separately, the two advisors will be compatible and will eventually interface with each other. Each of the advisors is being designed to be modular so additional heuristic knowledge can be easily added to expand the application of the advisors into other manufacturing processes. Development of these advisors has benefited from extensive software reuse. Not only do they share several modules between them, but they also incorporate code from Sandia's SmartWeld project (discussed elsewhere in this proceeding). Support of design engineers, casting experts, machining experts and other manufacturing experts is the key to the success of the advisors as the project develops.

Success of the project requires more than the development of two manufacturability advisors. Development of the prototype systems allows the project team to evaluate numerous design decisions of the approach, the knowledge-bases, and the user interfaces. The lessons learned from the development of these two advisors will be immense. The real success will be the application of these lessons to the design and improvement of current advisors and future advisors.

Application of heuristic, knowledge-based systems to manufacturing processes does not stop with these two advisors. Manufacturers are experiencing a competitive environment in which products are more complex, delivery times are shorter, and product life is shorter. Quality, durability, maintainability, safety, and environmental performance are becoming more and more important [Mantyla, Nau, & Shah, 1996]. Information must flow from the customer to engineering to manufacturing as accurately and quickly as possible. Application of heuristic, knowledge-based systems can aid in the flow of information. These two advisors can be expanded to incorporate improved, new and existing processes. Additional near net-shape processes, such as forging and power metallurgy, can be added to the *Near Net-Shape Advisor* to expand the functionality and encompass all areas of achieving rough shape. Expansion of the machinability advisor would incorporate other machining processes, geometric tolerance analysis, and extend the feature recognizer to deal with wall thickness.

With the knowledge gained from the development of these two advisors and the expansion of the feature recognizer, other advisors can be readily created to analyze other manufacturing methods, analysis, reliability, and assembly. Analysis advisors will help designers identify features that are detrimental to the durability of the system. Reliability advisors will help designers identify features that are difficult to maintain and processes that need to be improved. Assembly advisors will step through a complex tolerance analysis to determine the ability to be assembled of a system. Information can be passed quickly and accurately from one advisor to another and to the user. Mathematical models, CAD models, and knowledge-based models can be shared between manufacturing process advisors. These advisors will play important roles in what-if scenarios as design time is shortened and simulation becomes increasingly important. Also, the application of the heuristic, knowledge-based advisors will insure that design decisions are as accurate as possible to avoid costly redesign and meet or exceed the customer's requirements and expectations.

References

Guindon, R. 1990, Designing the Design Process: Exploiting Opportunistic Thoughts, *Human-Computer Interaction*, 5:305-344.

Ames, A. L. 1988, Automated Generation of Uniform Group Technology Part Codes From Solid Model Data, In Proceedings of the 1988 ASME International Computers in Engineering Conference and Exhibition, ASME.

Mantyla, M., Nau, D., and Shah, J. 1996, Challenges in Feature-Based Manufacturing Research, *Communications of the ACM*, February 1996, Vol. 39, No. 2, p 77 -85.

Dallas , D. 1976, Tool and Manufacturing Engineers Handbook, New York: McGraw-Hill.

Ames, A. L. 1991, Production Ready Feature Recognition Based Automatic Group Technology Part Coding, In Proceedings of the 1991 ACM Symposium on Solid Modeling Foundations and CAD/CAM Applications.