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Automated Manufacturability Analysis: A Survey

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Abstract

In the marketplace of the 21st century, there is no place for traditional "over-the-wall" communications between design and manufacturing. In order to "design it right the very first time," designers must ensure that their products are both functional and easy to manufacture. Software tools have had some successes in reducing the barriers between design and manufacturing. *Manufacturability analysis systems* are emerging as one such tool—enabling identification of potential manufacturing problems during the design phase and providing suggestions to designers on how to eliminate them.

In this paper, we provide a survey of current state of the art in automated manufacturability analysis. We present the historical context in which this area has emerged and outline characteristics to compare and classify various systems. We describe the two dominant approaches to automated manufacturability analysis and overview representative systems based on their application domain. We describe support tools that enhance the effectiveness of manufacturability analysis systems. Finally, we attempt to expose some of the existing research challenges and future directions.

1 Introduction

Increasing global competition is challenging the manufacturing industry to bring competitively priced, well-designed and well-manufactured products to market in a timely fashion. Although product design incurs only a small fraction of the total product cost, the decisions made during the design phase account for a significant portion of this cost [Ull92] and prove crucial to the success or failure of the product [Suh92, Whi90]. Since the cost of making design changes after initiation of the product development cycle escalates steeply with time, the ability to make essential changes during the design phase (as opposed to during the production run) translates into significant savings [Whi90]. To achieve this goal, increasing research attention is being directed toward the integration of engineering design and manufacturing. These attempts have led to the evolution of *design for manufacturability* (DFM) methodologies [Bak92]. DFM involves simultaneously considering design goals and manufacturing constraints in order to identify and alleviate manufacturing problems while the product is being designed; thereby reducing the lead time for product development and improving product quality.

Traditionally, the translation of a conceptual design into a final product to be manufactured has been accomplished by iterations between design and manufacturing engineers. Often, a designer would complete the entire design before passing the blueprints on to a manufacturing department. If the manufacturing engineers noticed any manufacturing-related problems, they would notify the design team and the design would be sent through another iteration.

To expedite these time-consuming iterations, a number of software tools have been developed—allowing designers to analyze manufacturability[1] during the design stage. In this paper, we collectively refer to such software tools as *automated manufacturability analysis systems*. Such systems vary significantly by approach, scope, and level of sophistication. At one end of the spectrum are software tools for providing estimates of the approximate manufacturing cost. At the other end are sophisticated tools that perform detailed design analyses and offer redesign suggestions. Automatic analysis of manufacturability during early design stages is a problem containing many challenging research issues, with an active and growing research community. While a large number of technical papers have been published, each covering important facets of this problem, there is no paper in the open literature that provides an overview of the advances that have been made in this area. In this paper, we attempt to provide a survey of the current state of the art in automated manufacturability analysis.

Manufacturing systems are extremely complex and touch on a wide variety of challenging research issues. Covering all facets of manufacturing systems and their relationship to automated manufacturability analysis in a single paper is not possible. This paper mainly focuses on fabrication processes such as machining, sheet metal manufacturing and the like. Metal cutting is the most widely researched fabrication process and many of the analysis systems we will discuss have

[1]There seems to be no universal definition of the term manufacturability. However in most cases, manufacturability refers to the design characteristics which indicate how difficult or easy the design is from manufacturing perspective.

been developed for machining. Most of the systems investigated in this study were developed in the United States. While many similar systems have been developed in Europe, Asia, and other parts of world, our limited resources restricted us to focus on the systems described in the academic research publications available in the United States. However, this study, while admittedly not globally complete, observes a wide enough variety of systems to infer current trends and practices.

The remainder of this paper has been organized as follows. Section 2 provides some of the historical context and technological developments behind the current interest in manufacturability analysis, with a particular focus on the developments in the United States. Section 3 introduces basic terminology and outlines general characteristics to compare and classify various systems. Section 4 gives an overview of representative work in manufacturability analysis for a variety of manufacturing processes—we provide brief summaries of representative manufacturability analysis systems discussed in open literature. Manufacturability analysis systems need to interact with a number of other software tools to exchange data and information. Section 5 discusses some of these related software tools that are needed to accomplish effective manufacturability analysis. Lastly, Section 6 attempts to expose some of the existing research challenges and future directions.

We expect that this paper will be of interest to a diverse group of readers: to experts, it will provide an overview of existing technology and help them compare their work with that of other efforts. To newcomers to this area, it will serve as a tutorial and provide references to many of the fundamental works. To industry and end-users, it will provide insight into a new and evolving family of software tools and expedite the transfer of these new technologies to commercial systems from academic prototypes.

2 Historical Perspective

The roots of DFM date back to World War II [ZS93], when scarcity of resources, coupled with constant social and political pressure to build better weapons in the shortest possible turnaround time, were the main motivating factors behind the tight integration of design and manufacturing activities. Many of the successful weapons of that period were designed by small, integrated, multi-disciplinary teams [ZS93]. With the post-World War II era of prosperity and the rapid industrial growth, design and manufacturing were segregated into distinct departments; resulting in a sequential product development environment with little attention to DFM. In the late 1970s, increasing global competition and the desire to reduce lead times led to the rediscovery of DFM. Some attempted to build inter-departmental design teams with representatives from both design and manufacturing departments. In these design projects, manufacturing engineers participated in the design process from the beginning and made suggestions about possible ways of improving manufacturability [GF90, Hol9o]. Such inter-departmental design teams did not always work harmoniously and many management-related problems existed when building and coordinating such teams [OYGS91].

In an attempt to increase designers' awareness of manufacturing considerations, leading professional societies have published a number of manufacturability guidelines for a variety of manufacturing processes [Bak92, Bol49, Bra86, PB84, Tru87]. Some companies produced and used their own guidebooks for designers (one of the pioneers was General Electric [Ele60]). These guidelines enumerated design configurations that posed manufacturability problems and were intended as training tools in DFM. To practice DFM, the designer had to carefully study these guidelines and try to avoid those configurations that resulted in poor manufacturability.

The availability of low-cost computational power is providing designers with a variety of CAD tools to help increase productivity and reduce time-consuming *build-test-redesign* iterations. Examples include tools for finite element analysis, mechanism analysis, simulation, and rapid and virtual prototyping. The availability of such tools has become a driving force for research in *concurrent engineering,* where various product life-cycle considerations are addressed at the design stage. As the advantages of concurrent engineering are being realized, more downstream activities associated with the various manufacturing aspects are being considered during the design phase—DFM is an important component in concurrent engineering environments [Whi90, Bak92].

One of the primary goals of concurrent engineering is to build an *intelligent CAD* system by embedding manufacturing related information into CAD systems. In an intelligent CAD system, DFM is achieved by performing automated *manufacturability analysis*—a process which involves analyzing the design for potential manufacturability problems and assessing its manufacturing cost. It is expected that these systems will alleviate the need to study and memorize manufacturability checklists, therefore allowing the designers to focus on the creative aspects of the design process. Moreover, as the manufacturing resources or practices change in an organization, the knowledge-bases of these intelligent CAD systems could be updated automatically with minimum interference with the design activities of the organization.

It has become evident that the task of manufacturability analysis requires extensive geometric reasoning. As the field of solid modeling has matured, functional and architectural improvements in modelers have facilitated increasingly sophisticated types of geometric reasoning. Because the closed architecture CAD and solid modeling systems of the 1980's did not allow easy access and manipulation of geometric and topological entities, most of the computer-aided DFM tools developed in that period did not rely on extensive geometric reasoning. This, in turn, limited their capacity for handling complex design shapes. In recent years, the functional capabilities of commercial systems have vastly improved. These new enhancements, coupled with the advent of parametric design systems[2] and open-architecture solid modeling systems [Spa93], facilitate implementation of the complex geometric reasoning techniques and systems integration required for realistic manufacturability analysis.

Manufacturability analysis is becoming an important component of CAD/CAM systems. Inadvertent designer errors, such as missing a corner radius or excessively tight requirements for surface finish, that go undetected during the design stage may prove costly to handle in a fully automated CAD/CAM system (i.e. the system might select an expensive manufacturing operation to achieve that erroneous design attribute). It is anticipated that a systematic methodology for manufacturability analysis will help in building systems to identify these types of problems at the design stage, and provide the designer with the opportunity to correct them.

3 Background and Defining Characteristics

Given a computerized representation of the design and a set of manufacturing resources, the automated manufacturability analysis problem can be defined as follows:

[2] Most notably, Parametric Technologies' Pro/ENGINEER was among the first on the market. In recent years, parametric tools have been incorporated into existing systems by most other major CAD vendors (including SDRC, Bentley, Intergraph, and Unigraphics to name only a few).

1. Determine whether or not the design (e.g., shape, dimensions, tolerances, surface finishes) is manufacturable.

2. If the design is found to be manufacturable, determine a *manufacturability rating*, to reflect the ease (or difficulty) with which the design can be manufactured.

3. If the design is not manufacturable, then identify the design attributes that pose manufacturability problems.

Three of the primary characteristics that distinguish various manufacturability systems from each other include what approach they take, what measure of manufacturability they use, and what level of automation they achieve. These three characteristics are described further below:

1. **Approach.** For analyzing the manufacturability of a design, the existing approaches can be classified roughly as follows:

   - In *direct* or *rule-based* approaches [Ish93, JP89, RDPD92], rules are used to identify infeasible design attributes from direct inspection of the design description. This approach is useful in domains such as near-net shape manufacturing. However, it is less suitable for machined or electro-mechanical components, in which interactions among manufacturing operations can make it difficult to determine the manufacturability of a design directly from the design description.
   - In *indirect* or *plan-based* approaches [HDW89, HS94, HGS93] the first step is to generate a manufacturing plan, and modify various portions of the plan in order to reduce its cost. If there is more than one possible plan, then the most promising plan should be used for analyzing manufacturability. These systems have wider applicability than do direct systems.

2. **Measure of Manufacturability.** There are many different scales—or combinations of scales—on which manufacturability can be measured:

   - *Binary measures.* This the most basic kind of manufacturability rating: it simply reports whether or not a given set of design attributes is manufacturable.
   - *Qualitative measures.* Here designs are given qualitative grades based on their manufacturability by a certain production process. For example, Ishii *et al.* [Ish93] rated designs as "poor," "average," "good," or "excellent." Some times such measures are hard to interpret—and in situations where the designer employs multiple manufacturability analysis tools (for example, one for machining and the other one for assembly), it becomes difficult to compare and combine the ratings from the two systems to obtain an overall rating.
   - *Abstract quantitative.* This type of scheme involves rating a design by assigning numerical ratings along some abstract scale. For example, Shankar *et al.* [SJ93] proposed a scheme in which each design attribute was assigned a manufacturability index between 1 and 2. Just as with qualitative measuring schemes, it can be difficult to interpret such measures or to compare and combine them.

- *Time and cost.* In general, a design's manufacturability is a measure of the effort required to manufacture the part according to the design specifications. Since all manufacturing operations have measurable time and cost, these can be used as an underlying basis to form a suitable manufacturability rating. Ratings based on time and cost can easily be combined into an overall rating. Moreover, they present a realistic view of the difficulty in manufacturing a proposed design and can be used to aid management in making make-or-buy decisions. These measures may not be directly helpful for determining if the designer has achieved satisfactory level of manufacturability in the design. To some extent, the target production time and cost can be used by the designer to help him in designing products that meet those targets.

With the exception of binary measures, all other currently available measures can be used to compare two alternative designs. However, in most cases they are not adequate for determining if a design has achieved satisfactory level of manufacturability. A design may be complex due to intended functionality and may require a large manufacturing effort. For example, an aircraft engine requires a large number of features to satisfy its intended functionality and therefore needs a large production time. On the other hand, a can opener requires very few features and therefore can be produced quite easily relative to the aircraft engine.

Existing measures seem to work satisfactorily when comparing two different designs of aircraft engines or comparing two different can openers. However, comparing manufacturability of an aircraft engine to that of a can opener is a different story. In order to have more meaningful measures of manufacturability, we need new measures which account for intended functionality and cost targets in measuring manufacturing.

3. **Level of automation.** This last characteristic involves how the designer interacts with the system and what type of information is provided to the designer as feedback.

   - *Amount and type of designer interaction.* In some systems (e.g., [JPU85]), the designer may need to enter a feature-based representation of the design in terms of the particular feature library used by the system. In more sophisticated systems, [NLR93a] the system works directly from the solid model of the design. If needed, feature-based representations are generated automatically.
   - *Amount and type of feedback information.* Most manufacturability analysis systems provide some kind of manufacturability rating of the design. Some systems provide detailed decomposition of the manufacturability ratings of various design attributes [GN95]. A few systems provide, along with the manufacturability rating, redesign suggestions to improve the design. Usually these are suggestions to change parameters of various design features [SD89], but some systems [HDW89] present redesign suggestions as complete redesigned parts.

4 Representative Systems

The manufacturability of a design is strongly dependent on the manufacturing processes used to create it. For example, a design that has an ideal shape for casting may not be suitable for machining. Hence, approaches to computer-aided manufacturability analysis are strongly influenced by the type of manufacturing processes they select to address. Below, we describe automated manufacturability analysis systems for several different types of manufacturing domains, including assembly (Section 4.1), machining (Section 4.2), printed circuit boards (Section 4.3), and other miscellaneous efforts (Section 4.4).

4.1 Assembly

Most early work on assembly analysis was rule-based: design attributes of the components, the assembly operations, and relationships between components were used to estimate the ease or difficulty of assembly of components. These rule-based approaches represented a breakthrough over the existing state of the art. Currently, however, more plan-based evaluation systems are being developed in order to better reason about situations where the particular assembly sequence greatly affects assemblability.

The pioneering work of Boothroyd and Dewhurst [BD83] in developing the design-for-assembly guidelines has resulted in several automated assembly evaluation and advisory systems [JP89, HGS93]. Swift [Swi81] also presented a methodology similar to that of Boothroyd and Dewhurst. Another effort in this direction was made by Jakiela *et al.* [JP89], who developed a design advisory system by integrating a rule-based system with a CAD system. Jakiela's system provides a library of predefined features with which the designer can create a design; when new features are added to the design, the system makes use of production rules to evaluate the design and offer suggestions for improving it. In their approach, the designer creates parts using the features offered by the library, working incrementally and, as the design progresses, offering advice at every design step. Hence, the design improvement suggestions are strongly influenced by the sequence in which the designer enters various features.

De Fazio and Whitney [DW87, DW88a] presented one of the first efforts to develop possible assembly sequences and selecting suitable ones using manufacturing information. They identify "liaisons" between components of the assembly. The "liaisons" represent connections or relations between assembly components, usually in the form of physical contacts like snaps and screws. From these liaisons, assembly precedences are identified and used to determine the feasible assembly sequences. The assembly sequences are generated from a disassembly state by adding components until a final assembly is generated. In most cases their algorithm generates multiple alternative sequences. The determination of precedence constraints is an interactive process and their methodology does not obtain them directly from a solid model. The algorithm needs to be extended to extract the liaisons automatically for use in an automated assemblability evaluation system.

Although the Hitachi Assemblability System [MO86, MOI90] was not initially computerized, over time it has served as a basis for development of an automated assemblability system. The Hitachi methodology is based on the principle of one motion per part; there are symbols for each type of assembly operation and penalties for each operation based on its difficulty. Finally, the method computes an *assembly evaluation score* and an *assembly-cost ratio*. This *assembly-cost ratio* gives an indication of cost per operation. By studying these results one can identify the sources of bad assemblability and, after modifications to the designs are made, these metrics can be recomputed to find the degree of improvement. The methodology is common for manual, automatic and robotic systems. One of the early success stories of this method is highlighted in [HMS+80].

Warnecke and Bassler [WB88] studied both functional and assembly characteristics. Parts with low functional value but high assembly difficulty receive low scores, while parts with high functionality and low assembly cost receive high scores. The scoring is used to guide the redesign process.

Miles *et al.* [MS92] developed an assembly evaluation method in which parts are divided into two groups based on functional importance: "category A" parts are required from the design specification, and "category B" parts are accessories. The goal of the method is to eliminate as many "category B" parts as possible through redesign. Analyses of feeding and fitting are carried out on the parts, with both results combined into a total score. This total is divided by the number of "category A" parts in order to calculate a final score. A proposed assembly sequence is used to perform fitting analysis.

Sturges *et al.* [SK92] have developed a semiautomated assembly evaluation methodology that attempts to overcome some of the limitations of the scheme proposed by Boothroyd and Dewhurst [BD83]. Currently, while lacking geometric reasoning capabilities, their system serves as an interactive environment to study the effect of various design configurations on assembly difficulty.

Li and Hwang [LH92] did a study of design for assembly and developed a semi-automated system which closely follows the Boothroyd-Dewhurst methodology. The analysis of assembly difficulty and cost estimation modules are a direct computer implementation of the DFA rules. Their methodology considers multiple assembly sequences and calculates the time for all of the feasible sequences. They perform limited feature recognition for assembly and obtain from the user the non-geometric information that will affect the assembly. The final result is a table which is roughly the same as a manual assembly worksheet. The authors argue that the assembly information developed quickly and in proper format will give the designer enough input to perform further analysis for design modification. The task of automated redesign is presented as a future goal.

Hsu *et al.* [HGS93] developed an approach to design-for-assembly that examines and evaluates assembly plans using three criteria: parallelism, assemblability, and redundancy. They evaluate assembly plans in an attempt to find problems with the assembly and, when possible, introduce modifications to improve the plan. If a better plan is found, the design is modified by splitting, combining or perturbing various components. This system is one of the first approaches in plan based assemblability evaluation and redesign suggestion generation for assembly. There are limitations of this approach and compared to the work of Boothroyd and Dewhurst [BD83] their assemblability evaluation criteria are restricted. They do not consider tolerance and surface finish issues and can only suggest minor modifications to design. Also, in the absence of any model of the functional requirements of the product, the modified design may not satisfy the designer's intent.

Recent work by Jared *et al.* [JLSS94] presented mathematical models for the assembly operations and a DFA system that performs geometric reasoning based on the model. In this way, they rely less on user input. Their system calculates a manufacturability index for individual components and fitting index between the components.

Boothroyd [Boo94] presents a review of design for manufacture and assembly methodologies in use at different companies.

4.2 Machining

Initially the efforts in machining sought to relate the different attributes of a part design to the manufacturing process so that design rules could be employed to asses manufacturability. Because of the very nature of the machining process, different operations almost always interact with each other; and because of these interactions it becomes very difficult to isolate instances to apply these rules. An additional complication is due to the fact that there usually exists more than one way of manufacturing the same part. In these cases it becomes nearly impossible to identify manufacturing problems with design rules alone. Currently the trend is towards plan-based systems. Earlier methods, with abstract rating schemes, are also yielding to more direct measures like time and cost. Due to the different kinds of variables involved in the machining process, this remains the most challenging domain.

Lu and Subramanyan [SL91] developed a manufacturability evaluation system for bearing cages. They addressed several aspects of the manufacturability problem including fixturing, tooling, gagging, and material handling. They used a multiple cooperative knowledge sources paradigm that separated domain knowledge from the control procedure. Their domain was restricted to parts with axi-symmetric features which can be manufactured on a lathe.

Priest and Sanchez [PS91, SPP92] developed an empirical method for measuring the manufacturability of machined parts. Their approach involves rating a design based on producibility rating factors. The producibility rating factor is calculated from considerations that influence producibility and observed production difficulties. They defined producibility rating factors for a variety of manufacturing considerations such as material availability, machinability tooling, material/process risk compatibility etc.

Hsiao *et al.* [Hsi91] developed a knowledge-base for performing manufacturability analysis of machined parts. Their approach is capable of incorporating user-defined features and represents machining processes by their elementary machining volumes and limitations on tool motion. For each design feature, they defined *constraint-face sets* that represent various machining faces and any neighboring faces that restrict the accessibility of the feature. Constraint-face sets are evaluated to determine if the feature can satisfy the conditions imposed by the elementary machinable volume and tool motion for the machining process. While their approach is capable of handling a limited number of accessibility constraints and tolerances, it does not consider the possibility of alternative features and does not provide any manufacturability rating scheme.

Anjanappa *et al.* [AKAN91, KAA91] developed a rapid prototyping system for machined parts that emphasized existing standards and available databases. The design is stored as an IGES file and a rule-based feature extractor is used to find machining features. The feature extractor is limited and no intersections among features are allowed. The manufacturability analyzer performs analysis based on the specific machining cell configuration for which the system was designed. The manufacturability rating does not calculate machining cost and time but it does match the features with tools, machines and fixtures. In addition, it lists those features that are non-manufacturable and those that are potentially difficult to manufacture. From these features, it also creates the NC machining code to machine the component. This system does not investigate the possible alternative ways of machining the same part.

Hitachi corporation [Miy91] extended their design for assembly methodology to also take into account machining processes. Together with their AEM method, this results in an overall producibility evaluation system. Boothroyd *et al.* [BR89] published a report on the evaluation of machining component during early design stage. They described two methodologies for arriving at cost estimates. The first methodology takes into account only part and stock geometry, batch size, material and component type. The second methodology uses more shop floor information. Each each case, the feedback is in terms of manufacturing cost.

Cutkosky and Tenenbaum [CT92] developed NEXT-Cut: a system for the design and manufacture of machined parts. Using NEXT-Cut, the designer can create a design by subtracting volumetric machining features corresponding to machining operations from a piece of stock material. As features are subtracted from the workpiece, the system uses its knowledge-base to analyze the design's manufacturability. If any of a variety of manufacturability constraints are violated, the designer is warned of the violating features. This system works directly with features defined by the designer and so it is incumbent upon the designer to describe the design in terms of the most appropriate set of features. NEXT-Cut requires that the designer have good knowledge about machining processes in order to select the most appropriate feature set for machining; failure to do so may produce incorrect analysis.

Yannoulakis *et al.* [YJW94, YJW91] developed a manufacturability evaluation system for axi-symmetric parts machined on turning centers. They did not consider parts with axi-asymmetric features such as threads. They created a feature-based description of the part and evaluated the manufacturability index of each feature. The manufacturability index was based on the estimated machining time of the feature; calculated with empirical techniques for estimating cutting parameters and machining time. Their method did not consider geometric tolerances or the possibility of alternative features. The final result from the manufacturability evaluation procedures employed by them is a set of different indices, each providing a different indicator about the manufacturability of the individual features and the complete overall part. Some of these indicators deal with the time spent in loading-unloading, fixturing and changing tools. One feature of their system is that it ranks the features as candidates for redesign based on the analysis results. A number of research issues such as feature accessibility, precedence constraints, setups, etc., need to be addressed in order to scale up their approach to prismatic parts.

Gupta *et al.* [GN95, GKN+94] describe a methodology for early evaluation of manufacturability for prismatic machining components. Their methodology identifies all machining operations which can be used to create a given design. Using those operations, different operation plans for machining the parts are generated. For each new operation plan generated, it is examined whether the plan can produce desired shape and tolerances. If the plan is capable of doing so, the manufacturability rating for the plan is calculated. If no operation plan can be found that is capable of producing the design, then the given design is considered unmachinable; otherwise, the manufacturability rating for the design is the rating of the best operation plan. The rating is based on estimated machining time for the part. Based on this approach, Das *et al.* [DGN94] reported a methodology of suggesting improvements to a given design to reduce the number of setups to machine a part. Their approach involved using different machining operations to satisfy the geometric constraints put on the part by the designer. These constraints are based on the functionality of the part. Later different modifications are combined to arrive at redesign suggestions.

There are many other research efforts in manufacturability analysis for machining. We briefly mention two others: Chen *et al.* [PL94] has developed a system for setup generation and feature sequencing. They use multiple objective functions for setup and tool sequence generation. Mill *et al.* [MNS94] devised a simultaneous engineering workstation.

4.3 Printed Circuit Boards

The role of the designer in the design of printed circuit boards (PCB) components is broader than in other domains. Usually the designer, based on what is commercially available, selects components; this selection in turn dictates the production method. Hence, printed circuit boards and their process plans are developed simultaneously. While ideal systems for manufacturability analysis are plan-based, rules are often better suited for certain sub-problems within this domain.

Similar to design for assembly, many major electronic manufacturers have taken the lead in developing metrics for evaluation of printed circuit board designs. NEC corporation [AKKI85], General Electric [Ska86] and Xerox [Xer79] have reported in-house systems for evaluating PCB designs and assemblies.

O'Grady *et al.* [OYGS91] developed a constraint-based system (LARRY) that addresses various life-cycle considerations during the design of printed wiring boards. They treat the design process as a constraint satisfaction problem where the various manufacturability considerations are represented as a constraint network. As the designer adds features to the design, the constraint network is evaluated for possible violations. If violations are found, the designer can either select different manufacturing resources or modify the feature that caused the violation. Their approach is computationally intensive: as more features are added to the design, the constraint network grows in size. Their system considers only drilling of holes on printed wiring boards and it is not clear how their approach will handle the computational problems posed by consideration of additional manufacturing operations.

Harhalakis *et al.* [HKMR93] developed a system for manufacturability evaluation of microwave modules. Their system works with a STEP form feature based representation of the design, and uses rough-cut process plans to assign a manufacturability rating on a scale from 1 to 10. This rating system was developed by interviewing the machinists on the shop floor and, while reflecting difficulty associated with manufacturing, there is no direct correspondence between the ratings and manufacturing cost or time. Their system has a limited capability to perform geometric reasoning to identify interacting features but the effects of precedence constraints, tool changes, setup costs, etc., are not considered in their evaluation criteria.

Other works in manufacturability analysis of PCBs include [RvT85, PD91, Str88, Bao88]. These efforts are for the most part for specific sub-domains of PCB manufacturing. Most are rule-based and, because of the fast pace of technological changes, these rule-bases need to be updated regularly. The majority of the state-of-the-art research in this area is happening within the manufacturing industry's research and development centers.

4.4 Miscellaneous Manufacturing Processes

Various near-net shape processes (e.g., casting, stamping, injection molding, sheet metal working) often have specific manufacturing defects associated with them. Rules are used to associate design attributes with the probability of a defect. Production occurs in two steps: first, the production engineer accounts for the manufacturability of the tooling; and second, assesses the manufacturability of the actual part. Near-net shape processes create parts in a manner that is particularly well suited for the use of rules to encode the relationships between design attributes to manufacturing processes. Rule-based systems have found success in near-net manufacturing domains and the recent trend is toward using knowledge of process physics and simulation to reason about manufacturability, looking for violations of design-for-manufacturability heuristics.

Ishii *et al.* [Ish93, AI89, IM92, IN89] have developed design-compatibility analysis tools to aid in designing products for various life-cycle considerations. In their approach, a set of design elements is defined for each life-cycle application. While the designer interactively identifies these elements in a proposed design, she is prompted to provide information about user and functional requirements. Their system uses a *compatibility knowledge-base* to evaluate tradeoffs between various design elements and functional requirements. A compatibility knowledge-base is a collection of domain-dependent rules used to calculate a compatibility index. If a design attribute receives a poor compatibility index, the system offers advice by illustrating predefined cases that result in good compatibility. Ishii and his colleagues have built a number of design advisory systems using this approach.

El-Gizawy *et al.* [EGHB90] presented a system which considers the suitability of different manufacturing processes for a given part based on a process capability database. Once a process is chosen, two types of analysis are performed: first a rule based analysis using knowledge- and rule-base, at which stage redesign suggestions are provided. These suggestions are not for the complete parts, but for portions of the design. Secondly, an analytic and experimental process simulation is performed to determine the time required to produce the part and its material requirements. The methodology also includes in its cost calculation the machining cost after a net shape process.

The work of Huh and Kim [HK91] describes a system for supporting concurrent design for injection molding. Their interactive expert system encodes rules for different molding materials and supports the synthesis of supplementary features to be put on to the initial design. The system aids the designer when performing tasks such as the determination of rib requirements, rib cross-sections, rib frequency and design of bosses. Both function and manufacturability are considered when providing help for these decisions. Interactive feedback is provided to the designer in two forms: first the probability of having different forms of manufacturing defects, such as sink marks, warpage, or ejection difficulty. The second type of feedback is in the form of a warning messages which suggest possible problems for the designer to avoid. The feedback is quantitative, giving the probability of occurrence of the manufacturing defects. This information is hard coded in the rules and the numbers that are calculated can only reflect the cases considered by the system.

Wozny *et al.* [WTD+91, WTG+92, WTG+93] have developed a unified representation to support evaluation of design for manufacturability. Their approach is broad and more complete than most others and considers multiple manufacturing processes when evaluating components. Evaluation is done hierarchically during the configuration and detailed design stages. In addition, they consider the functionality of the parts, tolerance information and also provide redesign suggestions. Finally, they also consider assembly of the components. Their approach integrates many phases of the design and manufacturing process.

Bourne [Bou92] reports work at Carnegie-Mellon University toward an "Intelligent Bending Workstation." Being developed in the same line as CMU's earlier Intelligent Machining Workstation project, they are implementing an open architecture model for a bending controller in order to overcome the common difficulties posed by closed NC machine controllers. This system will be customizable and extendable, allowing for future incorporation of additional modules.

Nnaji *et al.* [NLR93b] reported development of a complete product modeler for concurrent engineering. This modeling system builds product model with assembly, dimensioning and functionality consideration. It follows a set of part-to-part relations defined for assembly operations based on standard spatial relationships. The modeler also does manufacturability analysis for sheet-metal work and assembly. These analyses are based on production rules and collision relations, those do not include consideration of functionality.

Dissinger *et al.* [DM94] have developed a three-dimensional modeling system for designing powder metallurgy components. The part design is created layer by layer and, with the addition of each layer or a component to a layer, checks are made for possible manufacturing rule violations. The system is interactive, alerting the designer of the rule violations and giving suggestions for modifications. Finally the system allows only the design of manufacturable components.

Balasubramaniam *et al.* [SU94] proposed a method for developing producibility metrics for process-physics dominated production processes such as extrusion, injection molding etc. Their approach predicts the likelihood of common manufacturing defects based on different physical characteristics of the design. As an example they developed metrics for various types of defects in extruded aluminum components for aircraft. In this work, they conducted experimental and statistical verification of the metrics based on actual vendor data.

Shah and Rogers [SR94] present two different domains of manufacturability evaluation. The first system involves machining [SHR90], where alternative machining operations are evaluated and suitable ones chosen. Initially setup or sequencing issues are not considered. After selecting operations, two types of checks are performed: first, rule-based checking to find if there are violations of "good practice." During the second check, the cheapest possible feasible sequence of operations is found using branch and bound search technique and redesign suggestions are also presented. The feedback results are in terms of machining cost. Their second system involves forming methods of fiber-reinforced thermoplastics. It is a rule-based system which considers both the part manufacturing and the tooling. It also suggests redesigns in terms of parameters of the design features.

The Toshiba Corporation [TSSxx] is using a Processability Evaluation Method which works in tandem with an assemblability evaluation method. The cost of any part depends on the processing method with a rating calculated by examination of alternative processing methods. Cost is determined by using a combination of different processes and materials.

There are additional works reported by researchers on various types of net shape manufacturing, including injection molding [Dew87, GGH+91, IKD89, PC89, RDPD92, GS94], die casting [DB89], sheet metal work [TOHY85, ZD88, dSLEE93], casting [LDS86], powder metallurgy [Kni91], extrusion [HG86] and stamping [MPRW93].

Shankar *et al.* [SJ93] proposed a domain independent methodology to evaluate the manufacturability of designs based on a set of five core manufacturability concepts: compatibility, complexity, quality, efficiency, and coupling. Based on each of these concepts, they assign a manufacturability index to various attributes of the design. The overall manufacturability of the design is characterized by the sum of the indices for every attribute of the design. While this methodology addresses some of manufacturability issues, it considers no specific manufacturing process—thus it cannot determine whether a given design is manufacturable or not. In addition, their approach does not identify the design attributes that pose manufacturability problems.

5 Related Software Support Tools

In an intelligent CAD environment, manufacturability analysis systems will be interacting with a variety of other software tools. The effectiveness and efficiency of manufacturability analysis will depend on the capability of such supporting tools and nature of the interaction between manufacturability analysis systems and the other software tools.

In this section, we describe various software tools that will be used to support manufacturability analysis systems. In order to offer meaningful suggestions for design changes to improve its manufacturability, the manufacturability analysis system needs to have some notion of intended functionality of the design. Section 5.1 reviews some leading works in functionality representation. Most manufacturability analysis systems use feature-based representation of the design. Quite often, feature extraction systems are used to generate feature-based representations. Section 5.2 presents some discussion on the current research in feature-based design interpretations. In case of machining process, techniques very similar to that of generative process planning are used to perform manufacturability analysis. Section 5.3 gives an outline of research in generative process planning and related areas.

5.1 Functionality Representation

Manufacturability evaluation goes hand in hand with product redesign. This redesign process can be automatic, interactive or manual. In all such cases it is necessary to have a model of what the component under consideration is meant to accomplish. For this reason we expect future manufacturability evaluation systems to provide for some degree of functionality representation.

We present a brief introduction on how the functionality of a part can be represented in its CAD model. In most cases, the goal of research efforts on functionality representation has been the development of the representation itself; often the scope of the representation is very broad. In other efforts, the goals were specific to a class of products where the design attributes and functionality are intimately coupled.

Nielsen *et al.* [NDZ91] reported a system for iterative design where functionality is represented as the target values for different parameters. Thompson *et al.* [TL89] proposed a methodology for representing design rationale. Their design rationale included plans constructed for planning future products and design constraints identified during the design process.

Dighe *et al.* [DJW93, DJ92] developed a system for a specific range of products (injection molded product housing) where the basic functions are mounting and structural rigidity. Welch *et al.* [WD89] developed a system for sheet metal bracket design. The only functionality required in this domain was the load path—a task they successfully accomplished. Schiebeler *et al.* [SE93] described a knowledge-based design assistant. This system represented functionality as a graph where the features are the nodes. The edges between the features depend on functional relationship between the features.

El Maraghy *et al.* [EZC93] proposed and implemented a design scheme based on functional features. The functions are pre-defined into the features in the library. Such functional features are also the core of work of Schulte *et al.* [SWS93].

Henderson *et al.* [Hen93, HT93, Tay93] developed a system for conceptual modeling and representation of functionality, features, dimensions and tolerances within a solid modeling system. Their functionality representation is based on textual descriptions that annotate the geometric model. This representation cannot directly be used for automated redesign purposes, as it does not lend itself to geometric queries and design modifications. The model described is detailed and may serve as a valuable guide for future development of functional models for other purposes.

Sodhi and Turner argue that effective functionality representation can only be achieved at the assembly level of a product. They [ST94] present a state of the art survey of assembly modelling research which demonstrates some functional modelling. Gui *et al.* proposed [GM94] a bond graph-based system of assembly modeling from functional perspective.

There are other research works related to functionality, design history, design rationale representation, many of which are worth noting [AY89, CGI93, CM92, KS89, Kle93, LA89, Sch89]. Detailed presentation of this body of work is beyond the scope of this paper.

5.2 Feature-Based Design Interpretation

In order to perform manufacturability analysis, a product design must be interpreted in terms of manufacturing features. *Automated feature recognition* has become the preferred technique for producing such feature-based representations, having been successfully employed for a variety of applications including process planning and part code generation for group technology. These feature technologies rely heavily on the geometric and topological manipulation capabilities of solid modeling systems and deal predominantly with form or machining features.

Kyprianou [Kyp80] presented the first effort to use a combination of graph algorithms and grammars to parse solid models of parts for group coding. Kramer [Kra89] has presented a grammar-based method for extracting non-intersecting features for a class of $2\frac{1}{2}$-dimensional parts. Methods based on graph-grammars have been used to both recognize features [PFP89, SF90] and translate between differing feature representations [RDF92]. Peters [Pet93] analyzes the combinatorial complexity of graph and grammatical approaches to feature recognition and presents heuristics to reduce these costs. In another effort to to address combinatorial problems and handle realistic industrial designs, Gadh and Prinz [GP92] describe techniques for abstracting an approximation of the geometric and topological information in a solid model and finding features in the approximation. More recently, Regli *et al.* [RGN95] have outlined methods to utilize multiple distributed processors. Their initial results show that multi-processor techniques can be effectively employed to expand the class of mechanical designs that are feasible and produce improvements in system response times.

Woo [Woo82], in an early effort on feature extraction, proposed a method for finding general depression and protrusion features on a part through decomposing the convex hull of the solid model. The approach had several limitations, including the existence of pathological geometric cases in which the procedure would not converge. The non-convergence of Woo's approach has been solved in recent work by Kim [Kim92, KW92, WK94], whose system produces a decomposition of the convex hull of a part as general form features. Extension of this method from polyhedra to the more general surfaces required for realistic parts is currently under investigation [MK94].

Other volume decomposition approaches include the recent work by Sakurai [SC94]. Exhaustively, each combination of cells is matched against user-defined feature templates. While the method is capable of generating all alternative feature interpretations composed of the primitive cells, it does so at a large combinatorial cost.

The seminal work of Henderson [Hen84] employed rule-based systems on the feature recognition problem and has served as a foundation for more recent AI-based approaches. Henderson has also made extensive use of graph-based methodologies, first in [GH90] where graph-based algorithms are used to find protrusion and depression features. In Chuang and Henderson [CH90] use graph-based pattern matching to find feature patterns from part geometry and topology. Chuang and Henderson [CH91] were the first to explicitly address both computational complexity and decidability when defining the feature recognition problem. Their paper formalized the problem of recognition of features (including compound features) through parsing a graph-based representation of a part using a web grammar. Most recently, Gavankar and Henderson [PH92] adapted neural networks to recognize features from polyhedral objects. Also in this area, Peters [Pet92] describes techniques for training neural networks to recognize feature classes that can be customized by the end user. In a recent paper, Henderson *et al.* [HSS+94] surveys a variety of feature recognition methodologies.

Other graph-based methodologies include the work of De Floriani [De 89], who employed graph-based algorithms for finding bi-connected and tri-connected components to partition a polyhedral part into several varieties of protrusion and depression features. Joshi's [JC88] approach used subgraph isomorphism algorithms to match feature patterns to patterns in the topology of polyhedral parts. Sakurai [SG90] developed a graph-based system capable of handling limited types of user-defined features, providing for a degree of application-specific customizability. Corney and Clark [CC91, CC93] have had success extending the capabilities of graph-based algorithms to more general $2\frac{1}{2}$-dimensional parts. The work of Dong and Wozny [Don88, DW88b, DW91] included formalization of a feature description language and was the first to employ a frame-based reasoning system to extract machining features for computer-aided process planning. Their approach included the ability to construct volumetric features from surface features and perform an analysis of tool accessibility.

Karinthi and Nau [KN92] presented the first systematic work on the generation of alternative interpretations of the same object as different collections of volumetric features. They present an algebra for computing alternate interpretations of parts resulting from algebraic operations on the features.

The ability to recognize interacting features has been a goal of a number of numerous research efforts, among them [GP92, JC88, Don88]. The approach of Marefat [MK90, MK92] built on the representation scheme of Joshi [JC88] and used a combination of expert system and hypothesis testing techniques to extract surface features from polyhedral objects and handle a variety of their geometric interactions. Marefat argues that his approach is complete over a class of polyhedral features, i.e., that it generates all features in his class that can be found from the geometry of a part. Another recent approach [TK94] addresses completeness over a limited domain of iso-oriented polygonal parts. Regli *et al.* [RGN94, RN93] present a methodology for specifying the feature recognition problem and proving it is complete over a well-defined class of parts. Their features are based on a class of machining features that describe operations on three-axis machining centers and encompass a realistic class of parts bounded by analytic surfaces.

The most comprehensive approach to date for recognizing features and handling their interactions has been the OOFF system (Object-Oriented Feature Finder) of Vandenbrande [VR93]. Vandenbrande's work, using a knowledge-based approach like that of Dong and Wozny, provides a framework for recognizing machining features and building process plans via artificial intelligence techniques in combination with queries to a solid modeler.

Work of Laakko and Mäntylä [LM93] couples feature-based design and feature recognition to provide for incremental feature recognition. This type of approach identifies changes in the geometric model as new or modified features while preserving the existing feature information. They also provide for some form of customizability with use of a feature-definition language to add new features into the system.

Other related work includes feature recognition from 2D engineering drawings [MP93], feature recognition for sheet-metal components [LS93], and feature modeling by incremental recognition [LM93]. Many aspects of the feature recognition problem are still open and active areas of research. Among these are: recognizing and representing interacting features [VR93], incremental recognition of features [HR94], modeling alternative feature interpretations [MK90, RGN94], reasoning about the manufacturability of features [GN95, GKN+94], and incorporation of user-customizable feature classes.

5.3 Generative Process Planning

As mentioned in previous sections, many of the manufacturability evaluation systems use manufacturing plans to evaluate manufacturability. For this reason we include here a brief review of some representative systems of automated process planning.

Computer-aided process planning is a key element in integrating design and manufacturing [AZ89]. Many attempts have been made to automate process planning of machined parts [CT92, AZ89, BW94, Cha90, Nau87, GRT92, WL91]. The two traditional types of approach to computer-aided process planning are the *variant approach* and *generative approach*. The variant approach involves retrieving an existing plan for a similar part and making the necessary modifications to the plan for the new part. The generative approach involves generation of new process plans by means of decision logics and process knowledge. Most plan-based manufacturability analysis systems use generative techniques. Therefore, we will only discuss generative approach in this paper.

Usually, the task of generative process planning involves a number of inter-dependent activities, most of which cannot be performed independently. Generation of the optimal process plan usually requires several iterations and, although significant progress has been made, at present there are no automated process planning systems capable of automatically performing the complete planning task. This section only deals with those steps that are relevant to manufacturability analysis. For details and a literature survey on the complete plan generation steps, readers are referred to [AZ89, Cha90, WL91].

5.3.1 Process Selection

Process knowledge involves the shape producing capability and technological constraints for each of the available machining processes. A variety of knowledge representation techniques are used to model process knowledge, with production rules and frames among the most popular. Production rules involve condition-action sets, and are often expressed in the from of IF-THEN rules. Examples of systems using production rules include XCUT [BW94] and AMPS [Cha90]. Frames can represent both procedural and declarative information in terms of attributes, hierarchical relations with other frames, constraints, and procedures. SIPS [Nau87] and NEXT-Cut [CT92] use frames to represent process knowledge.

The process selection task is performed by examining the shape and tolerance requirements of an individual feature and selecting a process that is capable of meeting the requirements. Quite often, a feature needs a roughing operation followed by one or more finishing operations. Backward planning strategies have been successfully used to select the multiple operations needed for certain features. A number of process planning systems, among them AMPS [Cha90], SIPS [Nau87], use this technique to perform process selection.

5.3.2 Identifying Precedence Constraints

For a given part, the machining operations cannot be necessarily performed in any arbitrary order [GNRZ94]. Geometric and technological constraints will require that certain operations be performed before or after other operations.

AMPS [Cha90] uses heuristic techniques to determine precedence constraints among features. A number of rules based on machining practices have been defined and are used to determine precedence constraints among pairs of features. This approach allows for *strict* and *loose* constraints. Strict constraints cannot be violated, while loose constraints can—but at a detriment to ensuring good machining practice. The features in this approach are allowed to have multiple approach directions and may require conditional precedence constraints.

The Machinist system [HW89] is capable of handling the precedences that arise because of setup considerations. In this system, precedences are generated by examining the setup interactions among features. If the machining of a feature destroys the precondition for clamping during machining of another feature, then these two features interact and a precedence constraint exists.

Because of its closeness to well-known combinatorial optimization problems, optimization of operation sequences has received significant research attention. A number of systems have been developed that take precedence constraints as input and find the optimum operation sequence [PL94, PEWW]. However, most of these systems do not automatically generate the complete set of precedence constraints.

Precedence constraints are also important in generating and evaluating alternative assembly sequences. De Fazio and Whitney [DW87, NW89] provide some examples of that.

5.3.3 Fixturability and Setup Planning

To ensure successful machining, each intermediate workpiece shape should be fixturable. This requires consideration of fixturing devices and formulating the conditions that are needed to insure proper fixturing. Setup planning involves determining the various setups in which the part will be machined. While advances have been made in automated fixture design [Sak], existing research has mainly focused on designing new fixtures for a given geometry.

Chang [Cha90] presented comprehensive conditions for holding the workpiece in a vise. These conditions are based on the intermediate workpiece geometry and are sufficient for successfully clamping the workpiece. He also presented an algorithm for setup planning that, while producing valid results, in certain cases may generate setup plans that are non-optimal.

Yue and Murray [YM94] presented a comprehensive set of fixturability and clamping conditions for vise clamping, machine table clamping, and frame bolting for manufacture of 2.5D prismatic parts. These conditions are based on intermediate workpiece geometry and consider friction forces.

For a review of fixture design automation, readers are referred to articles [HK94, TL90].

5.3.4 Plan Evaluation

Plan evaluation consists of two main steps—verification and rating. Plan verification involves determining whether or not a plan is capable of meeting the design specifications. The main research issue in plan verification is determining the achievable manufacturing accuracy and comparing it with the design tolerances and surface finishes. Plan rating involves assigning a merit to the plan. If alternative plans exist, ratings are used to select the best plan.

Economics plays an important role in manufacturing planning. Estimation of cost and time has been an integral part of process planning activities [Cha90] and extensive research in machining economics has produced quantitative models for evaluating times and costs related to machining operations [Win89]. Various optimization techniques have been applied to these quantitative models to determine the machining parameters which minimize the variable cost, or maximize the production rate and profit rate [Aga92a, Aga92b, DH91, ZL90].

Each machining operation creates a feature which has certain geometric variations compared to its nominal geometry. Designers normally give design tolerance specifications on the nominal geometry to specify how large these variations are allowed to be. One needs to estimate accuracy of various manufacturing processes in order to verify whether or not a given process plan will produce the desired design tolerances.

In machining, various factors such as deformation of the workpiece and tool, vibration, thermal deformation, inaccuracies of machine tool, etc., affect the machining accuracy. Some of these factors are dependent on the selection of cutting parameters. For a limited number of machining processes, deterministic models have been developed to provide quantitative mappings between the cutting parameters (such as cutting speed, feed, and depth of cut) and machining accuracy (such as surface finish and dimensional accuracy) [WL91, NZGK93, ZK91a, ZK91b].

Zhang *et al.* presented [ZK91a, ZK91b, NZG92, ZH90] a comprehensive method for predicting the machining accuracy of turning and boring operations. Their methodology can be extended to model all machining processes involving single-point cutting tools. In complex machining operations, developing mathematical models is a very difficult task. In such cases, empirical methods are often used. Kline *et al.* [KDS82] proposed a system for predicting machining accuracy in end milling. Based on the past experiences of metal cutting industries, a significant amount of data has been published that describes the achievable machining accuracy of various machining processes [Bra86, Tru87, Cha90].

A *tolerance chart* is a tool for assessing machining accuracy. It is a graphical representation of the process sequence which helps to visualize the influence of the proposed sequence on resulting dimensions and tolerances. For each step of the the operation sequence, machining accuracy is estimated and tolerance stack-ups are calculated. Automated tolerance charting has not been incorporated into most automated process planning systems. Recently, attempts have been made to automate tolerance charting [Ji93, MIL90]. Current research on computer-aided tolerance charting focuses on calculation of optimum intermediate tolerances typically using linear programming techniques.

In near net shape processes and electro-mechanical component assemblies, the process physics often determine the accuracy and quality of the parts. Balasubramaniam *et al.* [SU94] provides some methods for determining possible manufacturing defects in aluminum extrusion. Similar works are also reported in other manufacturing processes.

6 Discussion

Today's marketplace is characterized by increasing global competition, shrinking product lifetimes, and increasing product complexity. Industries need to be able to quickly develop new and modified products, and to manufacture products at the right quality, at competitive costs (including environmental-protection-related costs as well as the usual production costs). This makes the design task more challenging, as designers must acquire and process a wide variety of design information and still meet ever-tightening deadlines. To assist designers with this expanded role, manufacturability analysis systems will need to be improved to meet the following performance criteria:

- **Scope.** As manufacturing industries adopt newer processes and materials, and participate in more collaborative manufacturing with suppliers and customers, the scope of manufacturability analysis systems will need to be expanded to take into account a variety of manufacturing issues that they do not currently address.

- **Accuracy.** In the analyses produced by a manufacturability analysis system are not sound, this can result in considerable delays and/or financial losses. For example, Petroski [Pet94] describes several cases in which design failures occurred because of errors made by software for analyzing design performance.

- **Speed.** Since design is an interactive process, speed is a critical factor in systems that enable designers to explore and experiment with alternative ideas during the design phase. Achieving interactivity requires an increasingly sophisticated allocation of computational resources in order to perform realistic design analyses and generate feedback in real time [RGN95].

With these criteria in mind, we present some specific issues that are important for future manufacturability analysis systems to address:

1. **Ability to handle multiple processes.** Many products are produced using a combination of different kinds of processes. For example, engine blocks are first cast, and then machined to final shape. Systems are being developed that handle more than one kind of manufacturing process [Ish93, NLR93b, SR94]. However, manufacturability requirements for different processes are often in conflict. For example, a design shape that is easy to cast may pose problems when fixturing it for machining. It will be necessary to develop ways to handle such conflicts.

2. **Alternative manufacturing plans.** In many cases it is possible to manufacture a part using different manufacturing processes or combination of processes. Thus to accurately determine the manufacturability of a product, it may be necessary to consider alternative ways of manufacturing it. In certain cases, there might be a large number of alternatives, making it infeasible to consider all of them. In order to preserve computational efficiency in such cases, methods are needed to discard unpromising alternatives while still producing correct results. Gupta and Nau [GN95] provide an approach to this problem in the context of machined parts—but methods still need to be developed for other manufacturing domains.

3. **Virtual enterprises and distributed manufacturing.** Manufacturing industries are relying increasingly on distributed manufacturing enterprises organized around multi-enterprise partnerships. In such environments, manufacturability analysis cannot be done accurately without taking into account the capabilities of the various partners that one might potentially use in order to manufacture the product. Projects are underway to address this problem (e.g., [NBG+94]), but the work in this area is still largely in its early stages.

4. **Process models and virtual manufacturing.** A static knowledge-base of manufacturing process capabilities may not be suitable for determining the manufacturability of a product in cases where the manufacturing processes are very complicated (such as near-net shape processes), or where the manufacturing technology is changing at a fast pace (such as composites processing). Projects such as [SU94, EGHB90] address this problem by analyzing manufacturability using data obtained from process models and manufacturing simulations. Some of the problems remaining to be solved include the development of better and up-to-date process models, and better integration of process models with manufacturability evaluation methods.

5. **Manufacturability rating schemes.** Fast decision-making regarding the manufacturability of proposed designs is becoming more important than ever. For helping designers and managers to make engineering and financial decisions, ratings of a qualitative or abstract nature will not be particularly useful—instead, the manufacturability ratings will need to reflect the cost and time needed to manufacture a proposed product, as done in [GN95]. We expect that future manufacturability rating schemes will not only represent production time and cost, but also provide detailed breakdowns of the time and cost of manufacturing various portions of the design. For such purposes, manufacturing-handbook data will not necessarily be accurate enough; instead, company-specific data (obtained, for example, via virtual [SU94, EGHB90] and physical [EGHB90, ZK91b] simulations) will be needed.

6. **Accounting for design tolerances.** Designers note dimensional and geometric tolerances on a design to specify the permissible variations from the nominal geometry that will be compatible with the design's functionality. Design tolerances are important aspect of the design and significantly affect manufacturability—but most existing systems have limited capabilities for analyzing the manufacturability of design tolerances. For example, most work on automated tolerance charting [Ji93, MIL90] focuses mainly on computing the optimum intermediate tolerances and has not been integrated with manufacturability analysis systems. In order to develop manufacturability analysis systems that are capable of handling problems posed by design tolerances, research in the area of estimating accuracy of parts made by different processes is essential.

7. **Automatic generation of suggestions for redesign.** For a manufacturability evaluation system to be effective, it is not always adequate to have the manufacturability rating of a component and a list of its production bottlenecks. Since designers often are not specialists in manufacturing process, they may not be able to rectify the problems identified by the manufacturability evaluation system. This is particularly true for cases where the part is manufactured by multiple manufacturing methods or is produced by a supplier. To address such problems, manufacturability analysis systems will need the ability to generate redesign suggestions.

   Most existing approaches for generating redesign suggestions [Ish93, SD89, HK91] propose design changes on a piecemeal basis, (e.g., by suggesting changes to individual feature parameters)—but because of interactions among various portions of the design, sometimes it is not possible to improve the manufacturability of the design without proposing a judiciously chosen *combination* of modifications. Also, existing systems usually do not take into account how the proposed changes will affect the functionality of the design. This will require the systems to be integrated with some form of functionality representation scheme and manufacturing database. Some work is being done to overcome both of these drawbacks [DGN94], but it is still in the early stages.

8. **Product life-cycle considerations.** For more comprehensive analysis of the total cost of a product, other life-cycle cost considerations also have to be taken into account [Ish94, IEH93]. Recently there has been a proliferation of tools for critiquing various aspects of a design (performance, manufacturability, assembly, maintenance, etc.). As designers begin to use multiple critiquing tools, we anticipate problems in coordinating these tools. Since different critiquing tools are written to address different manufacturing objectives, the recommendations given

by these tools will sometimes conflict with each other. Thus it will be necessary to develop ways to reconcile these conflicting objectives, so as to avoid giving the designer confusing and contradictory advice [GRN94].

9. **Making use of emerging information technologies.** Future manufacturability evaluation systems will need to make use of state-of-the-art developments in computer and information technology. Future CAD/CAM systems will be available on-line for users world-wide; in part as client-server systems, in part as manufacturing software services. New network software paradigms (as typified by the explosion of activity on the Internet and the World Wide Web) will require a radical rethinking of how to integrate and execute manufacturability analysis across the manufacturing business enterprise. Achieving high accuracy, comprehensive results, and fast response time will require the development of new methodologies for distributed systems integration for manufacturing applications [RGN95].

10. **System validation.** Very little has been reported about system validation in actual industrial settings. In order to asses effectiveness of automated manufacturability analysis systems, we will need in-depth testing and validations of such systems in industry.

11. **Human Computer Interaction.** In existing systems, little attention has been paid to human-computer interaction issues. In order to be effective and acceptable to designers, we will need systems that are designer-friendly and help in increasing his/her productivity. In many ways the current state of the art in CAD/CAM user interfaces is much like that of text/word processing in the late 1970s: different interfaces and functions, complex commands, and little commonality. As these systems evolve, the community will need to rigorously assess how to most efficiently and effectively present functionality to the user.

Conclusions. In this survey, we have attempted to present a cross-section of the results from the research community that has emerged to address the wide variety of problems faced when constructing automated manufacturability analysis systems. As evident in the above discussion, many important advances have been made. It is our belief that these successes demonstrate the huge potential impact that might be made by such systems.

However, there are a number of fundamental research challenges that need to be overcome in order to make automated design analysis tools realize their full potential. As evidenced by this survey, the current state-of-the-art contains many diverse, domain-specific systems. Each approach presents the community with a different aspect of the overall problem. Creating a truly interactive, multi-domain, multi-process system capable of satisfying the conflicting constraints posed by these domains and provide intelligent feedback and alternative suggestions to the designer. We are optimistic that the community is up to the challenges.

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