CONCLUSION

The manufacturing environment of an enterprise plays an important role in the generation of an effective process plan for a part. The manufacturing environment contains not only the manufacturing resource information, but also the manufacturing organization structure and capability of the enterprise. In this study, a representation scheme is introduced to effectively represent a manufacturing environment with the object-oriented technique. The concepts of manufacturing entity (ME) and working elements (WE) are introduced in the scheme. The scheme is general enough to be used in different enterprises.

Process planning is closely related to the manufacturing environment. A hierarchical structure to represent process plans is established by using the operating elements as its elements. An operating sheet is generated if a specific manufacturing entity is activated during process planning. The process plan model consists of operating sheets in a hierarchical structure related to the manufacturing entities activated. It is suitable for hierarchical decision making process. In this study, the knowledge information is embedded in a structured production rule system which uses both the frame and production rule concepts in representing detailed knowledge.

Due to the subjective behavior of process planning and the existence of multi-process plans, an event-driven architecture is more effective for a CAPP system to be designed with the event-driven mode. Compared to the sequential driven mode, the event-driven mode provides the necessary flexibility to the process plans so that they can intervene at any point of a planning process.

The aforementioned concepts have been implemented in a CAPP system, called U-CAPP. It is currently being used by a textile manufacturer in China.

REFERENCES


ABSTRACT

In the marketplace of the 21st century, there is no place for traditional over-the-wall communication between design and manufacturing. In order to "design it right the 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 survey current state of the art in automated manufacturability analysis. We describe the existing approaches to automated manufacturability analysis and overview representative systems based on their application domain. 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 determine a significant portion of the product cost [4], and can be crucial to the success or failure of the product [4]. Since the cost of making essential design changes escalates steeply with time, the ability to make crucial changes during the design phase translates into significant savings over making changes during production runs.

To achieve this goal, increasing research interest is being directed toward integrating engineering design and manufacturing. These attempts have led to the evolution of design for manufacturability (DFM) methodologies [2]. These involve 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 and improving the product quality.

Traditionally, the translation of the design concept into a final product has been accomplished by time-consuming iterations between design and manufacturing engineers. Often a designer would complete the entire design before passing the blueprint on to a manufacturing department. If the manufacturing engineers noticed any manufacturing related problems, they would notify designers and design would be sent through another iteration. To expedite these iterations, automated manufacturability analysis systems are being developed—allowing designers to analyze manufactura- bility during the design stage. Existing systems vary significantly by approach, scope, and level of sophistication. On one side of spectrum are software tools for estimating approximate manufacturing cost. At the other extreme are sophisticated tools that perform detailed design analyses and offer design suggestions. How to automatically analyze manufacturability during early design stages presents many challenging research problems.

Historical Perspective. The roots of DFM date back to World War II, when scarcity of resources, coupled with social and political pressures to build better weapons in the shortest possible time, led to the tight integration of design and manufacturing activities. Increasing global competition and demand to reduce lead times led to the rediscovery of DFM in the late 1970s. Some of the early attempts involved building inter-departmental design teams consisting of representatives from the design and manufacturing departments. In these design projects, manufacturability
In this paper, we provide a survey of current state of the art in automatic manufacture rating. It simply reports whether or not a given set of design attributes is manufacturable.

**Binary measures.** These have the basic kind of manufacturing capability of rating; they simply report whether or not a given set of design attributes is manufacturable.

**Qualitative measures.** These are also classified into binary and continuous measures. The former are generally easier to handle and typically report whether or not a given set of design attributes is manufacturable. The latter are generally easier to handle and typically report whether or not a given set of design attributes is manufacturable.

3. CURRENT TRENDS

The manufacturability of a design is strongly dependent on the manufacturing processes that are 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 that are used to create it. Below, we describe automatic manufacturability analysis systems that are designed for different manufacturing processes and environments.

3.1 Assembly

The early work in the analysis of assemblyability was rule-based. The design attributes of the components, assembly operations, and relationships between components are used to estimate the ease or difficulty of assembly of components. The design has been learned that the sequence of assembling components has a strong effect on the assembly process. As a consequence, more plan-based evaluation systems are being developed.

The pioneering work of Buntov and Dwork [32] in designing a system for assembling a DFA guidelines has resulted in several automated assembly evaluation and assembly systems [36, 20]. Another early effort in this direction was made by Jakobi et al. [26]. They integrated a DFA rule-based with a CAD system to develop a design for assembly system. This 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. This system works incrementally, as the design progresses, offering advice at every design stage.

Hence, the design improvement suggestions are strongly influenced by the sequence in which the designer enters various features.

Stenger et al. [36] have developed a semi-automated assembly evaluation method that attempts to overcome some of the limitations of the scheme proposed by Buntov and Dwork [32]. Currently, while lacking geometric reasoning capabilities, their system serves as an interactive environment to study the effect of various design configurations on assembly difficulty.

One of the first efforts in to develop possible assembly sequences and selecting suitable ones using manufacturing information was done by De Fazio and Whiteley [8]. Li and Hwang [31] did a study of design for assembly and developed a semi-automated system which closely follows the Boothroyd-Dewhurst methodology. Their analysis of is suggestions to change parameters of various assembly features [44], but some systems [17] present redesign suggestions as complete re-designed parts.
assembly difficulty and cost estimation modules are a double 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 non-geometric information that will affect the assembly. The methodology is in essence the same as a manual assembly worksheet. The authors show that the assembly information developed quickly and in properly the assembly survey of the system can be used to perform further analysis for design modification. The task of automated redesign is presented as a future goal.

Bessho et al. [22] developed a new approach to design for assembly that examines and evaluates assembly plans using three criteria: parallelism, assembly, and redundancy. They evaluate the plan to find the problems with the assembly. When possible, a better assembly plan is created by modifying the plan. If a better plan is found, the design is saved while the other plan is being updated, but if no better plan can be found, the design is updated by modifying existing parts. Some limited results are presented in an attempt to show the benefits of their approach.

Although the Etatsic Assembly Reliability System [38] was not initially implemented, over time it served as a basis for development of automated assembly evaluation systems. The methodology is based on the principle of one motor per part, there are symbols for each type of assembly operation and penalties for each operation based on difficulty. Finally, the Etatsic Assembly Reliability System also calculates assembly score and assembly costs ratio. The assembly measures also give an indication of current assembly costs to previous cost. The methodology should be used to assess assembly, automated, and robotic systems. One of the early success stories of this method is highlighted in [16].

The Etatsic Assembly Reliability System [38] also developed an assembly evaluation method in which parts are divided into two groups based on functional importance: category A parts are required from the beginning of the assembly and category B parts are not. The goal of the system is to ensure category B parts as possible through redesign. Analysis of feeding and fitting is carried out on category A parts, with parts resulting combined into a total score. This total score is divided by the number of category A parts to obtain a final average score. To perform fitting analysis a given proposed assembly sequence is used. Warburton and Basford [23] studied both functional and assembly characteristics of product design. Parts with low functional value but high assembly difficulty receive low scores. The methodology provides a useful tool for low assembly difficulty of high scores. The scoring developed by the system is used to guide the redesign process.

Boothroyd [5], who presents a review of design for manufacturing and assembly methodologies in use at different companies, divides the conditions into four main categories: pre-manufacturing, manufacturing, assembly, and testing. In conclusion, he states that pre-manufacturing is the most critical since it provides the foundation for the entire manufacturing process. He also states that the most critical aspect of the pre-manufacturing process is the design itself. The design must be able to withstand the stresses and strains of manufacture and assembly.

3.2. Near-Net Shape Manufacturing

For many high-value production applications, designs to be manufactured using near-net shape manufacturing processes (such as casting, forging, injection molding etc.) direct rule-based systems for part family design and manufacturing can prevent the design of parts from the fact that in near-net shape processes rules provide a powerful way to relate design and manufacturing attributes. These processes often have process-specific manufacturing features associated with them. In many cases, rules associate the design attributes to the probability of occurrence of different types of defects. The production process in near-net shape manufacturing is usually two step, one has to account for the manufacturability of the tooling, and the manufacturability of the part. Lately, manufacturers have been incorporating quality attributes into their design process by using near-net shape processes. Currently, near-net shape processes are used extensively for the manufacture of precision casting, and injection molding parts. Near-net shape processes provide a powerful way to relate design and manufacturing attributes. These processes often have process-specific manufacturing features associated with them. In many cases, rules associate the design attributes to the probability of occurrence of different types of defects. The production process in near-net shape manufacturing is usually two step, one has to account for the manufacturability of the tooling, and the manufacturability of the part. Lately, manufacturers have been incorporating quality attributes into their design process by using near-net shape processes.

Boothroyd et al. [10] have developed a three-dimensional modeling system for designing powder metallurgy components. The design process follows the basic characteristics of the system that a part 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, it alerts the designer of the manufacturing rule violations and provides suggestions for modifications. At the end of the system process that only manufacturable components are designed.

Bourne [6] reports work for an intelligent bending workstation. Being developed in the same line as intelligent machining workstations developed earlier, they are implementing an open architecture model for the bending controller to overcome the common difficulties posed by cloud control. The design methodology for the current system is open and extendable for future addition of other modules.

Balamurugan et al. [39] proposed a general method for developing productivity metrics for process-physics dominated production processes such as extrusion, injection molding etc. Their approach predicts the likelihood of common manufacturing defects using process physics-based design. As an example they developed metrics for various types of defects in extruded aluminum components for aircraft. They conducted experimental and statistical verification of the metrics based on actual vendor data.

3.3. Machining

For finding the manufacturability of components to be manufactured by machining, initially the effort was to relate the manufacturing parameters to the machinability index of the part. The machinability index is a measure that supports the synthesis of supplementary features to use in the design system. The index aids the designer when performing design tasks or in determining whether a given design is suitable for a given manufacturing process. It is used to determine the probability of a given process to work effectively on a given part.

In the present work, the current trend of the manufacturability index for machining is towards plan-based systems. Such systems are particularly well suited to handle the complex interactions among the machining operations. Also, the earlier methods of abstract rating systems model to different cutting parameters and cutting tool life factors which is a reasonable approach. The main challenge is to select influences of the different parameters that affect process time and cost. Due to the different kinds of variables involved in the machining process, this remains, by far the most challenging domain.

Beebe and Teichbaum [7] developed a NEXT-Cut: a system for the design and manufacture of machined parts. Using NEXT-Cut, the designer can create a design by selecting the manufacturing processes that should be used. NEXT-Cut makes sure that the machined parts can be manufactured from a piece of stock material. As feature are subtracted from the piece, the system uses its knowledge base to analyze the design's manufacturability. If any of a variety of manufacturability considerations are violated, the designer is warned of the violating feature. This system works directly with features defined by the designer and is a method for designing features that are manufacturable. If a feature is too expensive to manufacture, the designer is warned of the violating feature. This system works directly with features defined by the designer and is a method for designing features that are manufacturable. If a feature is too expensive to manufacture, the designer is warned of the violating feature.

Gupta et al. [24] describe a methodology for evaluation of manufacturability for machine components. Their methodology identifies all machining operations which can be used to create a given design. Using these 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 producing the design, then the given design is considered manufacturable; otherwise, the machining difficulty rating for the design is the rating for the best operation plan. The rating is based on estimated machining time for the part. Based on this approach, Dae et al. [25] have proposed a method for generating the rating for a given design to reduce the number of setups to machine a part. Their approach involved using different machining operations carried out simultaneously. Youn et al. [26] put on the part by the designer. These constraints are based on the functionality of the part. Later different modifications are continued to arrive at the final design.

Yannoulakis et al. [35] developed a manufacturability evaluation system for axisymmetric parts to be machined on turning centers. The part type study of the manufacturability did not consider any geometric features such as threads and splines. They created a feature-based description of the part and evaluate the manufacturability of each feature. They use the estimated machining time of the feature. They employ a number of empirical techniques to extract cutting data and cutting time but did not consider geometric tolerances or the possibility of alternative machining operations. The final result from the manufacturability evaluation provides a number of manufacturing cost indicators. These indicators give different types of information about the manufacturability of individual features and complete parts. Some of the
indicators deal with the comparative time spent in loading, unloading, fixtures and tool change. One of the features of their system is that the result of the analysis it ranks the features as candidates for redesign. A number of research issues such as feature accessibility, precedence con- straints, features tolerance, and CAD database are incorporated in order to scale up the approach to practical parts.

Lu and Subramanya [50] developed a manufacturability evaluation system that is based on the analysis of several aspects of manufacturability that included fixtures, tooling, parting, and material handling. They used a multi-objective development approach to obtain the desired goal. The domain knowledge from the process control procedure. Their domain was restricted to parts with axis-symmetrical features which can be manufactured on a lathe.

Piet and Sanchez [43] developed an empirical method for measuring the manufacturability of machined parts. Their approach involves using a design rule based on product design manufacturability rating factors. The manufacturability rating factor is calculated from considerations that influence producibility and control production difficulties. They defined four product design manufacturability rating factors for a variety of manufacturing considerations such as material availability, machinability, tooling, material and process risk compatibility etc.

Riano and Hiro [46] developed a knowledge-based for performing manufacturability analysis of machined parts. Their approach is capable of incorporating new features and represents manufacturing processes by their elementary machin- ing volumes and limitations on the tool motion. For each feature there are two sets of features that represent various machining faces and any neighboring faces that restrict the accessibility of the feature. These constraint faces are used to determine whether the feature can satisfy the constraints imposed by the elementary machining volume and tool motion for the machining process. While their approach is capable of handling a limited number of processes, they do not consider the possibility of alternative features and does not provide any scheme for computing a manufacturability rating.

Anjappa et al. [37] developed a rapid prototype system for machining parts. Their work emphasized using existing standards and available databases. For example, the design is stored as an IGES file and a rule-based feature extractor is used to find machining features. The set of features is limited and no intersections among features are allowed. A library performs analysis based on the specific machining cell configuration for which the system was designed. The manufacturability rating does not calculate tolerances but uses the features with tools, machines and fixtures. In addition, it lists those features that are non-manufacturable and those that are potentially manufactured. From these features, it also creates the NC machining code for machining of the component. This system does not investigate the possibility of altering the shape of the part.

Boothroyd et al. [4] 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 component type and does not consider specific manufacturability issues. The second methodology uses more shop floor information. The feedback to the designer is in terms of manufacturing cost.

3.4. Electro-Mechanical Components

In the domain of electro-mechanical components, the role of the designer is broader. Typically the designer selects different components from those that are commonly available. The selection of the components and their integration dictates the production method. In this way, both the product and the process plan are in a more developed stage. Ideally, systems for manufacturability analysis of electro- mechanical components are plan based. However, for a smaller subclass of problems within this domain, rules are often simpler and more appropriate. In general, many researchers are finding that rule-based methods are more suitable for the electronic sub-systems and plan-based methods are better for the mechanical components.

O'Grady et al. [39] developed a constraint-based system (LAREY) 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 new features to the design, the constraint network is evaluated for possible violations. If violations are detected, the designer either selects different manufacturing resources or modifies the feature that caused the violation. Their approach is computation- ally intensive and requires as an input 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 can handle the combinatorial problems posed by consideration of additional manufacturing operations.

Hathaway et al. [35] developed a system for manufacturability evaluation of microwave modules. Their system works with a STEP-based form feature representation of the design and uses a rough-cut process plan to assign a manufacturability rating. Their system is extended from 1 to 10. Their rating system was developed by interviewing the machinists on the shop floor. Though these ratings reflect difficulty associated with manufacturing, there is no direct correspondence between these ratings and manufacturing cost or time. Their system has a limited capability to perform geometric reasoning to identify interactions among features and the effects of precedence constraints, tool changes, setup costs, etc., are not considered in their evaluation criteria.

3.5. Other Miscellaneous Efforts

Sharar et al. [47] proposed a domain independent methodology to evaluate the manufacturability of design based on a set of five core manufacturability concept: 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 does not consider specific manufacturing processes—thus it cannot determine whether a given design is manufacturability cost efficient. The method does not identify the design attributes that pose a manufactureability problems.

Najaf et al. [38] reported development of a complete prod- uct model for a manufacturing system using CAD/CAM modeling system with a part model with assembly, dimensioning and function consideration. It follows a set of part-to-part relations defined for assembly operations in terms of spatial relationships. The model also does manufacturability analysis for sheet-metal work and assembly. These analyses are based on production ratio and collision relations but it does not include consideration of functionality.

El-Ghazaly et al. [31] presented a system which considers multiple design alternatives of the design for a given part. It does so based on a process capability database. Once a process is chosen two types of analyses is performed. First an analysis is performed using the knowledge and rule- base, at this stage redesign suggestions are also provided. These suggestions are not for complete parts, but for por- tions of the design. Finally a process simulation is per- formed both analytically and experimentally. It determines the time required to produce the part and material require- ments. The methodology also includes in its cost calculation the cost for machining operations which are needed after a set change process.

Moore et al. [46] present two different domains of manufacturability evaluation. The first one involves ma- chining [45]. Alternative machining operations are evaluated and a decision is made as to whether the setup or sequencing issues are not considered. After that two types of checks are done. Rule based checking is done to find out if there is any machining operation that is redundant. Then the least expensive machine for each type of processes are found using branch and bound technique. Based on this process redesign suggestions are also provided. The second domain of ma- chining cost. The second system involves forming methods of fiber-reinforced thermoplastics. It is a rule based system which considers both the part manufacturing cost and the tooling cost. It suggests redesigns in terms of parameters of the design features.

4. FUTURE CHALLENGES

The performance criteria for manufacturability analysis systems that have emerged include:

- Scope. As manufacturing industries adopt sewer processes and materials, and participate in more collabora- tions with manufacturers and customers, the scope of manufacturability analysis systems will need to be expanded to take into account a variety of manufac- turing options and consider the impacts of these options on the manufacturing process.
- Accuracy and reliability. If the results produced by a manufacturability analysis system are not sound, this can result in considerable delays and/or financial losses. Petrovic [46] describes several cases in which design failures occurred because of errors made by software for analyzing design performance.
- Correctness and completeness. It has emerged that the mathematical and computational foundations on which to precisely reason about geometric algo- rithms in design and manufacture are inadequate [14]. Several researchers have begun to approach this as a problem of complexity, which is increasing in- creasingly evident that further development of formal methods are intimately tied to improving the accuracy and reliability of manufacturing software systems.
- Integration. Analysis systems must interact with a diverse set of design and manufacturing software. Smooth integration of analysis with these many con- current activities has proven problematic.
- 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 stage. Achieving interactivity requires an increasingly sophisticated allocation of computational resources in order to perform realistic design analyses and generate feedback in real time [42].
- Sophistication of feedback. Cryptic manufacturability grades or large numbers of automatically generated alternatives do not assist the decision-making process. Users of these software tools require that the feedback provided be both correct and efficiently presented.

With these criteria in mind, we now discuss some specific issues that are important for manufacturability analysis sys- tems to address:

1. The capability to handle multiple processes. Many prod- ucts are produced using a combination of different kinds of processes. For example, engine blocks are first cast, then Machined to finish. Systems are being developed that handle more than one kind of manufacturing process [25, 38, 46]. However, manufacturability analysis systems for different types of processes are often in conflict. For example, a design that is easy to cast may pose problems when forging it for ma- chining. 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 but these processes may not be as efficient or cost effective as others. Thus to accurately determine the manufacturability of a product, it may be necessary to consider alternative ways of manufacturing it. In certain cases, these might be a large number of alternatives, making it infeasible to consider all of them. In order to preserve compu- tational efficiency in such cases, methods are needed to discard unpromising alternatives while still produc- ing correct results. [12] provides an approach to this
6. Accounting for design tolerances. Designers note dimensional and geometric tolerances on a design to upper the permissible variations from the nominal geometry that will be compatible with the design's functionality. Design tolerances are important aspects 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 [29, 34] focuses mostly 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 the accuracy of parts made by different processes is essential.

5. CONCLUSIONS

1. It is not always adequate to have the manufacturability ratings of a design, because it may not be able to rectify the problems identified by the manufacturability analysis system. This is particularly true for designs where the part is manufactured by multiple manufacturing methods or is produced by a supplier. To address such problems, manufacturability analysis systems will need to have the ability to generate redesign suggestions.

2. Most existing approaches for generating redesign suggestions [25, 44, 21] propose design changes on a piecewise basis, (e.g., by suggesting changes to individual features or 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 data base. Some work is being done to overcome both of these drawbacks [8], but it is still in the early stages.

3. Product life-cycle considerations. For more comprehensive analysis of the total cost of a product, other life-cycle considerations must be taken into account [22]. 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 also be necessary to develop ways to reconcile these conflicting objectives, so as not only to give the designer confusing and contradictory advice [13].

4. Making use of emerging technologies. Future manufacturability evaluation systems need to make use of state-of-the-art developments in computer and information technology. It is conceivable that in future these systems will be used worldwide. For achieving high accuracy at a fast response time the systems will be able to use computing capabilities at remote locations at a distributed manner.

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 products) [29, 13]. Computer-aided manufacturing technology is growing at a fast pace (such as computer-aided processing). Projects such as [49, 11] address this problem by analysing 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 required to manufacture a proposed product, as done in [12]. We expect that future manufacturability rating schemes will not only represent production feasibility but will also be detailed in breakdowns of the time and cost of manufacturing various portions of the design. For such purposes, manufacturing-handling codes will not necessarily be accurate enough; instead, company-specific data (obtained, for example, via virtual and physical simulations) will be necessary.

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 aspects 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 [29, 34] focuses mostly on computing the optimum intermediate tolerances and has not been integrated with manufacturability analysis systems. In order to


