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Current Trends and Future Challenges in Automated Manufacturability Analysis

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Abstract

In the marketplace of the 21st century, there is no place for traditional communications 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 of current state of the art in automated manufacturability analysis. We describe the two dominant 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.

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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 [51], and can be crucial to the success or failure of the product [53]. 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 run. To achieve this goal, increasing research attention 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 blueprints 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 manufacturability 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 redesign suggestions. How to automatically analyze manufacturability during early design states presents many challenging research problems. In recent years, a large number of technical papers have been published in this area.

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 desire 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, manufacturing engineers participated in the design process from the beginning and made suggestions about possible ways of improving manufacturability [17]. Such inter-departmental design teams did not always work harmoniously and many management-related problems existed when building and coordinating such teams [38].

In an attempt to increase the awareness among designers of manufacturing considerations, leading professional societies have published a number of manufacturability guidelines for a variety of manufacturing processes [2]. These guidelines enumerate design configurations that pose manufacturability problems and are intended as training tools in DFM. To practice DFM, the designer had to carefully study these guidelines and try to avoid those configurations that result in poor manufacturability.

Manufacturing Software. 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 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 and more downstream activities associated with the various manufacturing aspects are being considered during the design phase, and DFM has become an important part of concurrent engineering [53, 2].

In a concurrent engineering system, DFM is achieved by performing *automated manufacturability analysis*—involving analyzing the design for potential manufacturability problems and assessing its manufacturing cost. It has become evident that these analyses require 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. In recent years, the functional capabilities of commercial systems has been vastly improved. These new enhancements, coupled with the advent of open architecture and component software systems, facilitate implementation of the complex geometric reasoning techniques required for realistic manufacturability analysis.

Manufacturability Systems. 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 manufacturability analysis software tools 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.

In this paper, we provide a survey of current state of the art in automated manufacturability analysis and outline issues requiring future work. The paper is organized as follows: Section 2 outlines characteristics that can be used to compare and classify various systems. Section 3 gives an overview of representative work in manufacturability analysis for mechanical assembly, near-net shape manufacturing, machining, and electro-mechanical domains. Section 4 attempts to expose some of the existing research challenges and future directions. Lastly, Section 5 presents a brief conclusion.

2 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:

1. Determine whether or not the design attributes (e.g., shape, dimensions, tolerances, surface finishes) can be achieved.

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 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 [24, 25], 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 [16, 19] the first step is to generate a manufacturing plan, and modifying 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 design are given qualitative grades based on their manufacturability by a certain production process. For example, Ishii *et al.* [24] rated designs as "poor," "average," "good," or "excellent,". 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.* [46] 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 a overall rating. Moreover, they present a realistic view of the difficulty in manufacturing a proposed design and can be used to aide management in making make-or-buy decisions.

3. **Level of automation.** This involves how 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., [26]), 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, [36] 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 [11]. 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 [43], but some systems [16] present redesign suggestions as complete redesigned parts.

3 Current Trends

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 3.1), machining (Section 3.3), near-net shape manufacturing (Section 3.2), electro-mechanical components (Section 3.4), and other efforts (Section 3.5).

3.1 Assembly

Much of the early work in the analysis of assemblability 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. It has been learned that the sequence of assembling components has a strong effect on the assemblability. As a consequence, more plan-based evaluation systems are being developed.

The pioneering work of Boothroyd and Dewhurst [3] in developing the design-for-assembly guidelines has resulted in several automated assembly evaluation and advisory systems [25, 19]. Another early effort in this direction was made by Jakiela *et al* [25]. They integrated a rule-based system with a CAD system to develop a design advisory 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. In this approach, the designer designs the parts using the features offered by the library. This system works incrementally. 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.

Sturges *et al.* [47] have developed a semi-automated assembly evaluation methodology that attempts to overcome some of the limitations of the scheme proposed by Boothroyd and Dewhurst [3]. 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 [30] 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 the 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.

One of the first efforts in to develop possible assembly sequences and selecting suitable ones using manufacturing information was done by De Fazio and Whitney [8]. Hsu *et al.* [19] developed an approach to design-for-assembly that examines and evaluates assembly plans using three criteria: parallelism, assemblability, 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 modified by splitting, combining or perturbing various components. Although limited in certain ways, this offers a new plan based approach.

Although the Hitachi Assemblability System [34] was not initially computerized, over time it served as a basis for development of automated assemblability system. The 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 assembly-cost ratio. The assembly-cost ratio gives an indication of current assembly cost to previous cost. The methodology is common for manual, automatic and robotic systems. One of the early success stories of this method is highlighted in [15].

Miles *et al.* [32] 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 design specification, and "category B" parts are accessories. The goal is to eliminate as many type B parts as possible through redesign. Analyses of feeding and fitting is carried out on the parts, with both results combined into a total score. This total is divided by the number of type A parts to obtain a final score. A proposed assembly sequence is used. to perform fitting analysis.

Warnecke and Bassler [52] 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.

Recently Jared *et al.* [27] 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.

3.2 Near-Net Shape Manufacturing

For near-net shape manufacturing processes (such as casting, forging, injection molding etc.), the trend is toward direct systems. The reason for this stems from the fact that in near-net shape processes rules provide a powerful way to relate design and manufacturing attributes. However the recent trend is to use knowledge of process physics and simulation to determine manufacturability. These processes often have process-specific manufacturing defects associated with them. In many cases, rules associate the design attributes to the probability of occurrence of different types of defects. The production process is also usually two step, one has to account for the manufacturability of the tooling, and the manufacturability of the actual part to realistically determine manufacturability.

Ishii *et al.* [24, 22, 23] have developed design-compatability 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 *compatability 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 compatability.

Ishii and his colleagues have built a number of design advisory systems using this approach. This task of designing parts and specifying interactions among the features can be tedious and the system can be improved in that regard. Also the methodology does not appear to be suitable in cases where the interaction among features are very high or the design might have multiple interpretation.

The work of Huh and Kim [20] 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 aides the designer when performing tasks such as rib requirement, rib cross-section, rib frequency and in 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 is 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 message which suggests possible problems for the designer to avoid. The feedback is quantitative, in the sense that it gives probability of occurrence of common manufacturing defects. However this information is hard coded in the rules and the numbers that are calculated can only reflect the cases considered by the system.

For net shape manufacturing operations (e.g. casting, stamping, injection molding, sheet metal working) several manufacturability evaluation systems have been developed. Most of these systems use rule-based approaches to examine the violation of design-for-manufacturability heuristics.

Dissinger *et al.* [9] have developed a three-dimensional modeling system for designing powder metallurgy components. The design process follows the basic characteristics of a part created by powder metallurgy: the 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, alerting the designer of the rule violations and giving suggestions for modifications. Finally the system allows only the design of manufacturable components.

Bourne [5] reports work for an intelligent bending workstation. Being developed in the same line as intelligent machining workstation developed earlier, they are implementing an open architecture model for the bending controller to overcome the common difficulties posed by closed controllers in NC machines. This system will be customizable and extendable for future addition of other modules.

Balasubramaniam *et al.* [48] proposed a general 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. They conducted experimental and statistical verification of the metrics based on actual vendor data.

3.3 Machining

Initially the effort was to relate the different attributes of a part design to the manufacturing process in such a way to use design rules to find manufacturability. Because of the very nature of machining process, the different operations almost always interact with each other and it becomes very difficult to isolate instances to apply these rules. Also there usually exists more that one way of manufacturing the same part. In those cases it is impossible to use just design rules to identify manufacturing problems.

The trend in machining is towards plan-based systems. Such systems are particularly well suited to handle the complex interactions among the manufacturing operations. Also the earlier methods of abstract rating systems are giving way to direct measures like time and cost. Due to the different kinds of variables involved in the machining process, this remains, by far the most challenging domain.

Cutkosky and Tenenbaum [6] 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 considerations 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. This requires the designer have good knowledge about machining processes in order to select the most appropriate set for machining, as failure to do so may produce incorrect analysis.

Gupta *et al.* [11] 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.* [7] 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.

Yannoulakis *et al.* [54] developed a manufacturability evaluation system for axis-symmetric parts to be machined on turning centers. The part types under consideration did not include axis-symmetric features such as threads and splines. They created a feature-based description of the part and evaluated the manufacturability index of each feature. This manufacturability index was based on the estimated machining time of the feature. They employed a number of empirical techniques to estimate cutting parameters and machining time but 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. These indices gives different types of indications for manufacturability of individual features and complete parts. Some of the indicators deal with the comparative time spent in loading-unloading, fixturing and tool change. One of the feature of their system is that based on the result of the analysis it ranks the features as candidates for redesign. 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.

Lu and Subramanyan [49] developed a manufacturability evaluation system for bearing cages. They addressed several aspects of manufacturability that included fixturing, tooling, gaging, 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 axis-symmetric features which can be manufactured on a lathe.

Priest and Sanchez [42] 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.* [18] 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 the tool motion. For each design feature, they defined *constraint-face sets* for representing various machining faces and any neighboring faces that restrict the accessibility of the feature. These 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 scheme for computing a manufacturability rating.

Anjanappa *et al.* [1, 29] developed a rapid prototyping system for machined 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. 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 matches 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 for machining of the component. This system does not investigate the possibility of alternative ways of machining the same 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 stock geometry, batch size, material and component type. The second methodology uses more shop floor information. The feedback is in terms of manufacturing cost.

3.4 Electro-Mechanical

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

O'Grady *et al.* [38] 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 constraint satisfaction problem where the various manufacturability considerations are represented as a constraint network. As 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.* [14] 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. 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 interacting features and the effects of precedence constraints, tool changes, setup costs, etc., are not considered in their evaluation criteria.

3.5 Other Miscellaneous Efforts

Shankar *et al.* [46] 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, but 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.

Nnaji *et al.* [37] 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.

El-Gizawy *et al.* [10] presented a system which considers suitability of different manufacturing processes for a given part. It does so based on a process capability database. Once a process is chosen two types of analysis is performed. First a rule based analysis using knowledge and rule base is done, at this stage redesign suggestions are also provided. These suggestions are not for complete parts, but for portions of the design. Finally a process simulation is performed both analytically and experimentally. It determines the time required to produce the part and material requirements. The methodology also includes in its cost calculation the machining cost after a net shape process.

Shah and Rogers [45] presents two different domains of manufacturability evaluation. The first one involves machining [44]. Alternative machining operations are evaluated first and suitable ones chosen. At this stage setup or sequencing issues are not considered. After that two types of checks are done. Rule based checking is done to find if there is any good practice violation. Then the cheapest possible feasible sequence of processes are found using branch and bound technique. Based on this process redesign suggestions are also presented. The result is in terms of machining cost. The 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 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 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 and reliability.** In the results produced by a manufacturability analysis system are not sound, this can result in considerable delays and/or financial losses. Petroski [39] 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 rigorously reason about geometric algorithms in design and manufacture are inadequate [13]. Several researchers have begun to approach this as a problem of completeness [31, 41, 50]. It is becoming increasingly 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 concurrent 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 phase. Achieving interactivity requires an increasingly sophisticated allocation of computational resources in order to perform realistic design analyses and generate feedback in real time [40].

- **Sophistication of feedback.** Cryptic "manufacturability grades" or large numbers of automatically generated alternative design suggestions can be counter-productive. Users of these software tools require that the feedback provided is both correct and effectively presented to the designer.

With these criteria in mind, we now discuss some specific issues that are important for 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 [24, 37, 45]. 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. [11] provides 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., [35]), 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 [48, 10] 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 [11]. 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 and physical 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 [28, 33] 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 [24, 43, 20] 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 data base. Some work is being done to overcome both of these drawbacks [7], 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 [21]. 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 [12].

9. **Making use of emerging technologies.** Future manufacturability evaluation systems will 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 available on-line for users world-wide.

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.

5 Conclusions

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.

In this survey, we have attempted to present a cross-section of 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. The ultimate objective is to create 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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