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Design for Manufacture by Multi-Enterprise Partnerships

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Introduction

Recent world-wide political and financial events have intensified the need to renew the competitiveness of the US manufacturing industry. The means for enabling competitiveness include fast response to the market needs for new designs and re-designs, and the ability to manufacture products at the right quality and at competitive costs. To pursue market and technology opportunities effectively, US commercial and defense industries will be relying increasingly on multi-enterprise partnerships [Nevins 89]. Horizontal partnering combines the strengths of multiple firms in product design, manufacture, after sales support and customer service, in order to launch superior products in the global market.

To support effective partnering, new approaches will be needed for integrating the activities of design, planning, and production. Furthermore, it is important to address both the fundamental modeling of design, process planning, and production planning in ways that account for the capabilities of potential manufacturing partners, and the development of optimization procedures to address the underlying decision problems. This paper elaborates on these issues and discusses approaches for addressing them.

Computer Support for Design Automation

Traditionally, the design process has involved two main activities: synthesis and analysis. Most current CAD tools are geared towards analysis—but researchers have begun to investigate the possibility of automating some aspects of synthesis as well. Most of these activities can be classified roughly as follows:

- *Catalog-searching problems,* i.e., design problems which require selection of standard components. Considerable automation has been achieved in such problems. Currently, only a limited number of catalogs are available on-line, but we anticipate that these types of tools will gain more and more popularity.
- *Parametric design,* in which the physical configuration of the design is known or can be easily derived from the functional requirements [MacMahon 92], and the designer is mainly concerned with choosing the appropriate parameters for the design. Some successes have already been reported in automating this kind of design problem, and we believe that it is a promising candidate for further automation.
- *Creative design,* in which the designer does not know the physical configuration of the design, and must design it from scratch. Several research projects have reported interesting preliminary results (for example, see [Sycara 92])—but there is a striking contrast between the relative success of automated design techniques for certain electronic problems (such as the design of integrated circuits) and the relative lack of success of automated design techniques for mechanical and electro-mechanical devices. We believe that the primary reason for this discrepancy is that for mechanical and electro-mechanical devices, it is much more difficult to decouple the interactions among the device requirements than it is for purely electrical devices. Thus, we believe that the best approach will be not to try to automate the design task completely, but instead to develop tools for critiquing the design as it is being developed. Analysis tools will be needed to help the designer to foresee potential problems with a variety of life-cycle considerations, such as performance, producibility, partner selection, reliability, maintainability, and so forth. Research is already underway to develop such tools [Cutkosky 93, Gadh 91, Gupta 94, Hsu 93].

In a multi-enterprise partnership, products often are designed by one company and are manufactured jointly with other companies—and sometimes, even portions of the design task may be subcontracted to the manufacturing partners. Thus, design critiquing systems will be needed for advice at two different levels: (1) during the preliminary design stage, to critique the proposed design with respect to manufacturing resources of different potential partners, so that the optimal combination of manufacturing partners can be selected, and (2) to do detailed design critiquing once the partners have been selected, by utilizing critiquing systems based on the manufacturing resources of the selected partners.

As designers make increasing use of multiple critiquing systems, there will be problems in coordinating these tools [Klein 91]. For example, the design that is easiest to assemble is not likely to be the design that is easiest to machine. Thus if the designer follows the advice of a design-for-machinability tool, this may cause problems with assemblability, and vice versa. It will be necessary to develop ways to reconcile such conflicting objectives, so as to avoid giving the designer confusing and contradictory advice.

Process Planning

A conceptual model for process planning is one of the key issues in the concurrent engineering approach to product development. Computer-aided process planning (CAPP) functions must be modularized and distributed throughout the product and process design phases. For multi-enterprise partnering, the traditional approaches of programming all planning functions into a CAPP system which is used for after-design and before-production activities will not work well. In other words, simply interfacing results from existing CAD systems will not yield any useful tools for concurrent product development which requires design and planning functions be truly integrated at their task level. In this paper, we propose a new approach, namely, planning at the aggregate level.

In most manufacturing environments, process planning is done at two levels: the factory level and the detailed level. However, to account for the capabilities of potential manufacturing partners, process planning will need to be extended to incorporate an additional third level, the *aggregate* level. Whereas a "traditional" process plan defines operations to be carried out on certain machine classes, a multi-enterprise, aggregate process plan would define sets of operations, or simply aggregate operations, that must be carried out by factory classes. It is at the aggregate level that potential manufacturing partners would be identified and evaluated. Just as factory-level planning is done before detailed planning, aggregate-level planning would be done before factory-level planning.

The two primary techniques for doing process planning are the variant and generative approaches; for a survey, see [Ham 88]. Variant process planning has generally been much more successful at producing realistic process plans, but both it and generative process planning have some well known limitations. For near-term progress in process planning methodology, we envision that the most effective approach will be a hybrid approach that incorporates elements of both variant and generative process planning. More specifically, a hybrid approach to process planning would use variant techniques to retrieve process plans for existing designs that are similar to the new one, and use these plans as a starting point for synthesizing a final plan for the new design. Such a synthesis could be based on an analysis of the manufacturing processes involved—and this analysis could also be used to provide feedback about the manufacturability of the design. This hybrid approach should be able to combine the best features of variant and generative process planning, while avoiding the worst of the problems that they have individually.

Manufacturability Evaluation

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time—and thus it is important to design the product in such a way as to balance the need for efficient manufacturing against the need for a quality product. The idea of design for manufacturability has been around since World War II [Nevins 89], but progress in developing scientific methods has been slow. One of the goals of concurrent engineering is to identify design elements that pose problems for manufacturing and quality control, and provide feedback to the designer about these elements, so that manufacturability can be assured during the design stage. Most existing approaches to automated manufacturability evaluation involve rule-based systems that operate off-line; see [NSF 93] for examples.

For better predictions of manufacturability, it will be important to develop accurate models of manufacturing process behavior. We see two primary ways in which this can be done:

- Integrating deterministic and stochastic aspects to formulate modeling strategies to predict process performance. If such an approach were used to implement tools that could be used on-line while the design process is going on, this would provide a powerful consultation tool for evaluating manufacturability. As a step in this direction, we have developed physics-based models that incorporate both deterministic and stochastic aspects of manufacturing process behavior for machining operations [Zhang 91].
- Evaluating the manufacturability of a proposed design involves estimating the production cost and quality associated with manufacturing it. Since there can be several different ways to manufacture a proposed design, it is important to consider different ways to manufacture it, in order to determine which one best meets the manufacturing objectives. As a first step, we have developed a methodology for systematically generating and evaluating alternative operation plans for machined parts [Gupta 94].

By incorporating evaluation of economic aspects of the manufacturing process, we will have certain criteria that will play a central role in systematically evaluating the net worth of benefits among alternatives. Not only do the design and production engineers need the technical and scientific background for process planning, but they have to recognize the need to make necessary compromises and adjustments that will enable a realistic, although possibly not perfect, process plan to be achieved.

In a multi-enterprise partnership, manufacturability evaluation gains a new dimension. The partnership is able to multiply the effectiveness of efforts to harness resources to satisfy the product realization process in terms of engineers, machines, and materials. It also provides a great opportunity to achieve maximum financial success through proper planning and coordinations. The significance of evaluating manufacturability to achieve optimal combination of partners is demonstrated in the following section.

Multi-Enterprise Partnering

In addition to the challenges described above, concurrent engineering teams have to address the issue of synthesizing the optimum network of partners that will contribute to the realization of the proposed product design. Partner selection may no longer be performed by the purchasing department alone and should be based on an analytical foundation, rather than impressions, biases, or just cost. Within the emerging reality of vertical partnering, such decisions are becoming intrinsically coupled to the design activity.

The manufacturability evaluation approach described in the previous section will enable a concurrent engineering team to evaluate the manufacturing complexity, approximate manufacturing cost and cycle time, and achievable quality of their design with respect to the capabilities of a multiplicity of potential manufacturing partners. This evaluation will be based on the alternative process plans developed by the methodology described in the *Process Planning* section, and will consider the information captured in a partner manufacturing model. Selecting an aggregate process plan should be done concurrently with partner selection since the merits of a process plan can only be evaluated relative to the manufacturer who will carry it out. Clearly, there is a need for new models to support these decision problems. Such models would select an aggregate process plan and would assign activities to either in-house plants or specific partners. In addition, the sequence of activities and flow of materials among plants and partners would have to be determined. In assigning an activity to either an in-house plant or to a partner, two classes of criteria would have to be considered:

1. *The merits of assigning a particular activity to a particular plant or partner.* Some of the relevant considerations here would include cost, quality and cycle time. Any procedure used should recognize that some important criteria, for example some of the possible criteria for judging quality, might be hard to quantify.
2. *The overall merits of the activity assignments when viewed as an integrated system.* Several issues might be considered, such as the transportation and logistical requirements between partners, the capacity of individual partners relative to overall required throughput, and system reliability. For example, it may be desirable to include requirements for "partner redundancy" to avoid too great a dependency on any individual partner. To restrict overall system complexity, constraints could be imposed on the maximum number of partners or the geographic area within which the partner plants should belong.

Solution procedures should accommodate a variety of measures of system quality as well as the qualitative nature of some criteria. For example, the user should be able to guide the search for the optimum by providing preferred performance attributes, and be able to examine the recommended alternatives at any desired depth.

An additional advantage of having established and assessed alternative production options is the capability to react, in case of cost overruns or time delays during the execution of the preferred production plan. If such deviations are excessive, then re-planning may be necessary and the remaining alternatives should be re-examined. Re-planning is more complex than the problem of selecting the optimum set of partners. The production state, as well as cost and time constraints should be considered in this case. We intend to enhance our research in production planning using Petri nets [Harhalakis 94] to address this problem.

Database Environments for Manufacturing

It is now widely accepted that complex manufacturing tasks require the integration of information from a wide variety of heterogeneous sources. This problem is compounded even further by the emergence of virtual manufacturing enterprises organized around multi-enterprise partnerships. Such partnerships require integration of product, process, and business data both within and across multiple enterprises.

The object-oriented (OO) data model and database environment are well-suited for manufacturing systems management. Many of the problems with the use of relational databases for manufacturing applications such as CAD motivated the development of the OO data model; hence, much work has already been carried out in the OO modeling of manufacturing data for specific design problems.

We propose the development of OO data models and environments that allow for the integration of broad classes of manufacturing design data. This will require the definition, within the OO paradigm, of the structural and behavioral aspects of manufacturing data. It will also require close consideration of both the various on-going manufacturing data standards activities, e.g., the STEP standard, and the structure of existing data environments, e.g., MRP data. Finally, since one of the principal features of OO database systems is that they store both the *processes* of the modeled system as well as the data, it will be necessary to model manufacturing design processes and the manner in which the processes interact with the data. This work will impact manufacturing design in several ways:

- Integrated models can have easy access to disparate data sources. This will reduce the overhead of constructing interfaces for a variety of data sources and sinks.
- There is rapid technology development both on group decision making tools and high speed communications systems. Appropriate data models and database systems will allow these technologies to be used by concurrent engineering teams, especially geographically dispersed groups.
- Complex interprocedure data flows and algorithmic constructs such as feedback, can be efficiently and accurately implemented. For example, versioning of intermediate solutions, which is fundamental to the design of man-machine systems, could be readily implemented using OO database constructs.
- By using constructs such as "active" database features which trigger the execution of processes in real time, OO database systems would not only improve manufacturing control and manufacturing design systems individually, but also provide an environment for a tight integration between them [Haritsa 93].

Conclusions

US manufacturing industries are relying increasingly on virtual manufacturing enterprises organized around multi-enterprise partnerships. In order to develop tools to support such activities, we foresee the need for advances such as the following:

- the development of data environments in which integrated models can have easy access to disparate data sources;
- the development of hybrid variant/generative approaches for process planning;
- the development of aggregate-level models of designs, process plans, and production plans; and
- the development of optimization models for evaluating manufacturing alternatives, analyzing tradeoffs to find the best overall balance among conflicting design and manufacturing goals.

Research on these issues will serve as the basis for powerful concurrent engineering tools for providing feedback on design performance and manufacturability, and for evaluating production alternatives taking into account the capabilities of potential partners. Such tools are necessary to streamline the synthesis of partnerships in pursuit of technological and market opportunities. Tools of this type, together with advances in telecommunications and database systems, would provide an infrastructure for fast, effective formation of multi-enterprise partnerships that could provide a significant competitive advantage for US firms in the 1990's and beyond.

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CAE Applications in South Africa with Reference to Sport Stadiums and Gold Mining

K. E. Bruinette, D. J. Burger

Introduction

The South African engineering and electronic industries have kept abreast with developments worldwide. The major international electronic companies have subsidiaries in South Africa, and most of the software groups are represented. The departments of engineering at the various South African universities are recognised world wide, including in the USA, and graduates from these schools are allowed into international and USA universities for post graduate studies. These mechanisms keep the engineering and electronic industries up to date.

Present CAE Status in South Africa

The major hardware presently available in South Africa is from IBM, Sun Micro Systems, Hewlett-Packard, Silicon Graphics, Olivetti, Cray and the comparable French, German, British and Japanese products. The software used is mostly of British or USA origin, and is well supported by well-trained, knowledgeable technicians. Various South African packages have been developed for post-tensioned floor slabs and general structural analysis for use in building and bridge construction, as well as computer-aided drafting systems. One of these systems is being marketed in the USA.

The software suites are mostly discrete programmes with some integrated suites. AutoCAD and its related packages are very popular and consist of architectural, civil and sanitary engineering, structural and mechanical and electrical engineering packages that can be used on a discrete basis. Structural engineering packages to analyze and design slabs, columns, beams, footings, frames and girders with finite elements are used widely, i.e., Prokon suites. Extensive application of pull-down menus and interactive graphics make this package extremely user-friendly and productive.

The Integraph suite is also popular and is a more integrated system.

The discrete systems also contain software packages for the analysis of electrical circuits and systems; mechanical, i.e., ventilation and air conditioning; elevator; and electronic systems. Architectural packages include layout and elevation projection as well as elevation generation of interiors on a walk-through-mode assisting in conceptual design, etc. Discrete programmes are also available for the optimisation of designs in all these disciplines. In structural engineering, programmes are available to optimise the design in order to minimise cost, or to minimise time of erection, etc. This applies to all the other disciplines as well. Further programmes are available to generate details, i.e., rebar schedules, workshop details, steel drawings, profile and plate cut template generation, etc.

In all these programmes, a single subsystem, i.e., a single discipline or an extracted detail, is considered and defined. The total design is still to be articulated by interaction where human judgement and intervention are important. A drawback is that the geometrical input for the system may be very involved, cumbersome and time-consuming, and the interface between the systems and the professionals is not logical or takes time and is cumbersome.

Future CAE Systems

The ideal CAE system will have to be a totally integrated system that is interactive with the design team with visual display at all times or stages.

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14

INTEGRATED DESIGN AND PROCESS PLANNING FOR MICROWAVE MODULES

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14.1 INTRODUCTION

The standard product development process includes the conversion of functional requirements to design specifications, conceptual design, detailed design, process planning, production planning, and, finally, production. However, decisions made during the early phases of the process commit a large percentage of the total product cost. Thus, designers need tools that support concurrent engineering at all stages of product development, from conceptual and preliminary design through detailed design and manufacturing planning. In general, existing CAD/CAM tools are useful only during or after the detailed design stage. Moreover, existing preliminary and conceptual design tools support only the capture of design specifications.

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This chapter identifies the important issues in integrating design and planning of microwave modules and discusses our research efforts related to these issues. Although achieving complete design and planning integration is necessarily a long-range goal, this research explores the relevant issues, provides insight into the design and planning process, and develops sophisticated methods that can integrate the design and planning of microwave modules and other complex electromechanical systems.

14.1.1 Microwave Modules

Most commercial electronic products operate in the 10-kHz-to-1-GHz radio frequency spectrum. However, in the telecommunications arena, the range of operation frequency has been increasing at a tremendous pace. For scientific and commercial long-range defense applications—such as radar, satellite communications, and long-distance television and telephone signal transmissions—radio frequencies prove unsuitable, primarily due to the high noise-to-signal ratio associated with radio frequencies. Moreover, the lower-frequency bands have become overcrowded due to the overuse of these bands for commercial communications applications.[33]

Consequently, in contrast to other commercial electronic products, most modern telecommunications systems operate in the 1–20-GHz microwave range, and modules of such systems are termed microwave modules (see Fig. 14.1).

In earlier microwave circuit assemblies, different parts of the circuit were built separately using coaxial cables or waveguides and later assembled by fastening the parts together. Due to the size and configuration of the coaxial cables and waveguides, these were large and heavy assemblies, and the assembly procedure was a time-consuming and costly process. These earlier assemblies were replaced by microwave integrated circuits (MICs), in which all functional components of the circuit are fabricated as artwork on the same planar board, using the same fabrication technology. The artwork lies on the dielectric substrate, which lies on the metallic ground plane that also serves as a heat sink. Functional components such as transistors, resistors, and capacitors can be classified as either "integrated" or "hybrid." Integrated components are fabricated as a geometric manifestation of the artwork. Hybrid components are assembled separately using techniques such as soldering, wire bonding, and ultrasonic bonding. If all functional elements of the device are integrated, such devices are known as monolithic microwave integrated circuits (MMICs).

The production method depends on several factors, some of which are the choice of dielectric material and the degree of integration of functional elements in the design. If all elements are assembled as hybrids, then lamination, photomask deposition, etching, plating, adhesive deposition, application of flux, reflow soldering, trimming, cleaning, testing, tuning, drilling, milling, and casting form a superset of the operations used.[3, 7] If, however, some components are fabricated as integrated elements, then the product requires both thin-film and thick-film deposition.[19]

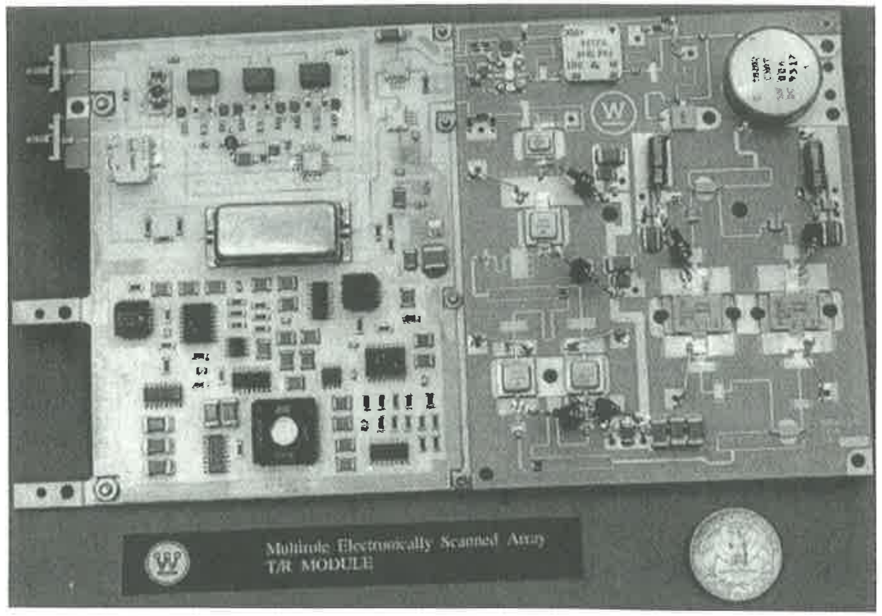

Figure 14.1 Typical microwave module.

14.1.2 Motivation

The design and manufacturing cycle for microwave modules is shown in Figure 14.2. Electronics designers develop the detailed circuitry; mechanical designers design the device to resist shock and vibrational loadings and they also develop the assemblies, the heat removal systems, and the housing of the device; and manufacturing engineers plan the electronics-related manufacturing processes (such as lithography, soldering, cleaning, and testing) and the mechanical processes (such as drilling and milling) to manufacture the end product. These are not independent decisions: For microwave modules, mechanical properties such as component placement and artwork dimensions affect electrical behavior. This interrelationship further complicates the design and manufacturing cycle.

The task of communicating design and manufacturing requirements and design changes across disciplines could be greatly aided by tools that integrate both electronic and mechanical computer-aided design and provide access to process planning and design evaluation capabilities, as shown in Figure 14.3. A designer could use such tools for both the electronic and the mechanical aspects of a product, analyzing various aspects of the design's performance,

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14

INTEGRATED DESIGN AND PROCESS PLANNING FOR MICROWAVE MODULES

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This chapter identifies the important issues in integrating design and planning of microwave modules and discusses our research efforts related to these issues. Although achieving complete design and planning integration is necessarily a long-range goal, this research explores the relevant issues, provides insight into the design and planning process, and develops sophisticated methods that can integrate the design and planning of microwave modules and other complex electromechanical systems.

14.1.1 Microwave Modules

Most commercial electronic products operate in the 10-kHz-to-1-GHz radio frequency spectrum. However, in the telecommunications arena, the range of operation frequency has been increasing at a tremendous pace. For scientific and commercial long-range defense applications—such as radar, satellite communications, and long-distance television and telephone signal transmissions—radio frequencies prove unsuitable, primarily due to the high noise-to-signal ratio associated with radio frequencies. Moreover, the lower-frequency bands have become overcrowded due to the overuse of these bands for commercial communications applications.[33]

Consequently, in contrast to other commercial electronic products, most modern telecommunications systems operate in the 1–20-GHz microwave range, and modules of such systems are termed microwave modules (see Fig. 14.1).

In earlier microwave circuit assemblies, different parts of the circuit were built separately using coaxial cables or waveguides and later assembled by fastening the parts together. Due to the size and configuration of the coaxial cables and waveguides, these were large and heavy assemblies, and the assembly procedure was a time-consuming and costly process. These earlier assemblies were replaced by microwave integrated circuits (MICs), in which all functional components of the circuit are fabricated as artwork on the same planar board, using the same fabrication technology. The artwork lies on the dielectric substrate, which lies on the metallic ground plane that also serves as a heat sink. Functional components such as transistors, resistors, and capacitors can be classified as either "integrated" or "hybrid." Integrated components are fabricated as a geometric manifestation of the artwork. Hybrid components are assembled separately using techniques such as soldering, wire bonding, and ultrasonic bonding. If all functional elements of the device are integrated, such devices are known as monolithic microwave integrated circuits (MMICs).

The production method depends on several factors, some of which are the choice of dielectric material and the degree of integration of functional elements in the design. If all elements are assembled as hybrids, then lamination, photomask deposition, etching, plating, adhesive deposition, application of flux, reflow soldering, trimming, cleaning, testing, tuning, drilling, milling, and casting form a superset of the operations used.[3, 7] If, however, some components are fabricated as integrated elements, then the product requires both thin-film and thick-film deposition.[19]

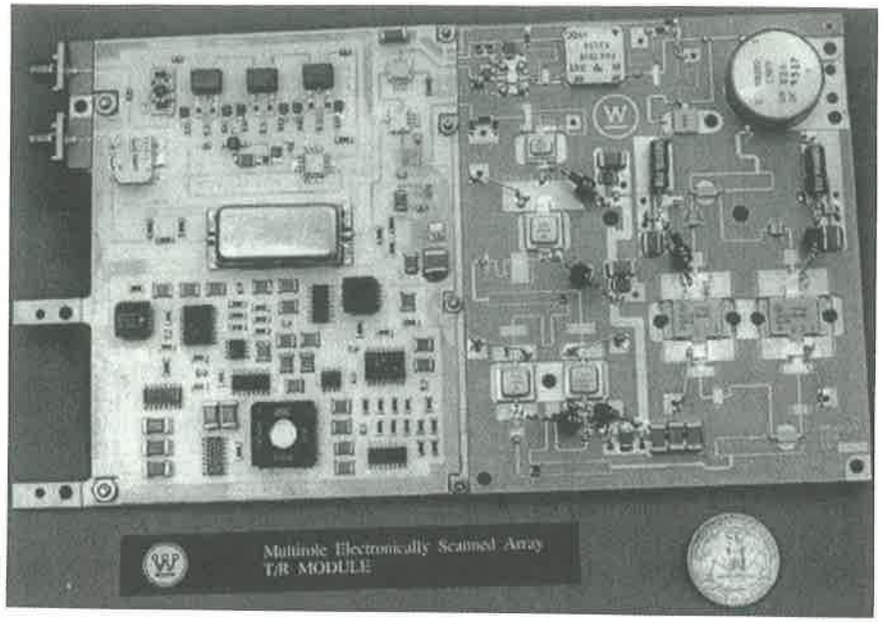

Figure 14.1 Typical microwave module.

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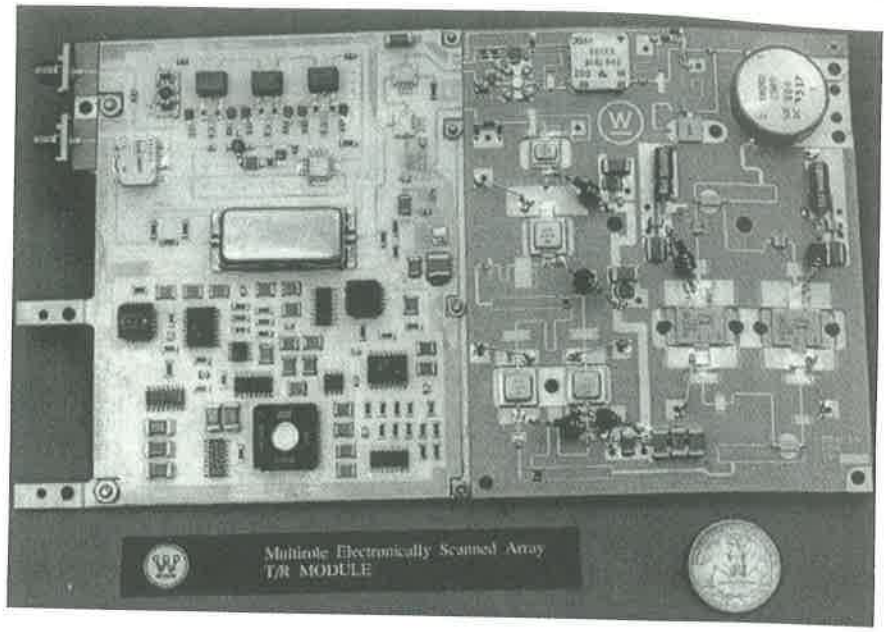

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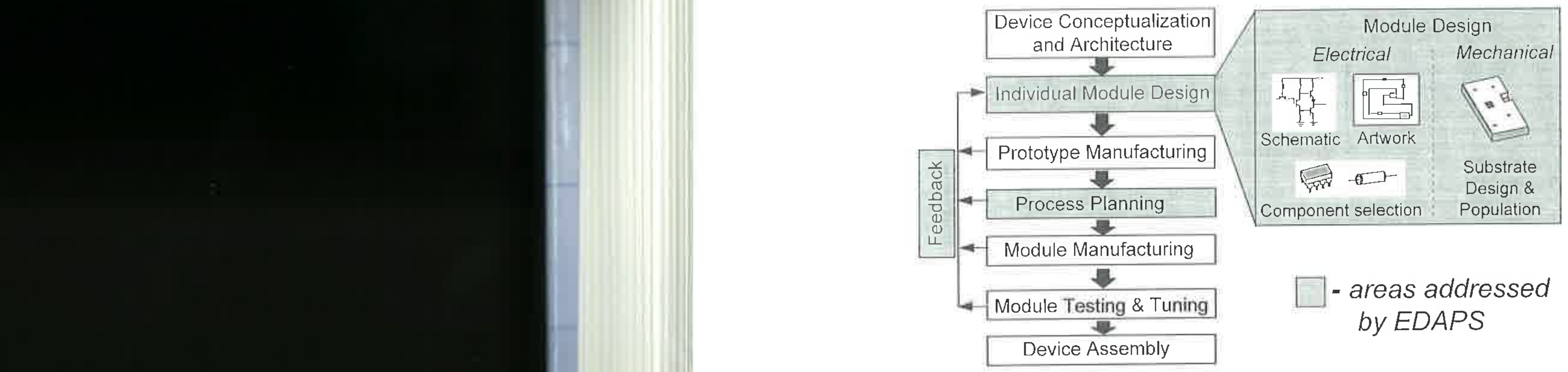

Figure 14.2 Design and manufacturing cycle for microwave modules.

planning how to manufacture the proposed design, and evaluating the plans to obtain feedback about the design. Throughout the design and manufacturing cycle, the designer is faced with the task of choosing among competing alternatives.

Consider first the typical case in which the manufacturer both designs and fabricates the microwave module. In this case, a number of choices are available for a given schematic, including alternate components, vendors, and processes. For example, a resistor of given specifications could be available as both leaded and surface mount types, and offered by a number of vendors with differing cost and quality ratings. These differences could, in turn, require different processes for assembly (board placement) and electrical connection (soldering). Also, the designer may need to evaluate both manual as well as automated options to carry out processes such as assembly and soldering. Additionally, there may exist quantity discounts and other intangible benefits associated with placing orders with a small number of suppliers—a fact that should be taken into account when choosing the components. The preceding factors therefore indicate that designers are typically faced with a large number of options in terms of component–process configurations and furthermore, there are cost and quality trade-offs between the various choices. Consequently, along with the manufacturability tools reported in the literature, there is a distinct need for models that efficiently explore the search space to identify "good" design options in terms of cost, quality, and other metrics.

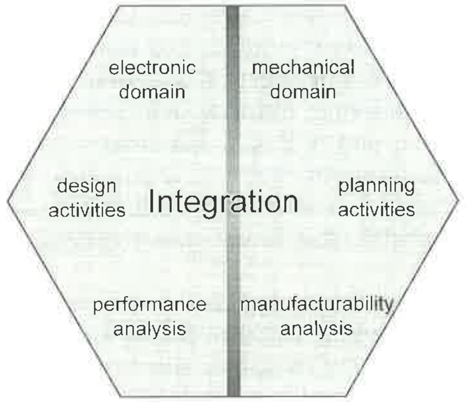

Figure 14.3 Integration of disciplines for design and manufacture of complex electromechanical devices.

Consider now the manufacturing firm's need to respond quickly to a market opportunity. The firm may wish to form a partnership with other manufacturers who may realize a portion of the product design and who cooperate to lower the product cost, improve its quality, and reduce the time span necessary to bring the product to market. Such a partnership may be a virtual enterprise: The partners electronically exchange the necessary information for design, process planning, production planning, inventory management, testing, distribution, and billing. Therefore, in addition to the design and manufacturing process described previously, the manufacturing firm must select the partners that can best realize the product. This goes beyond the classic make-or-buy decision. In addition, partner selection has design implications, because the designer should consider, during the early design phases, the partner-specific strengths that are related to the product's manufacturing requirements.

At this point, one can identify some required capabilities for integrated design and planning tools that support designers of complex electromechanical systems:

1. To manage alternative design and planning options throughout the design process.
2. To identify feasible options that designers might otherwise ignore and to provide information that they need to choose the best option.
3. To provide seamless access to external information sources such as CAD systems, design evaluation modules, parts catalogs, and supplier databases.

These requirements exceed the features of existing design support tools. Existing CAD/CAM tools are useful only during or after the detailed design stage. Designers need support during preliminary and conceptual design as well. Existing tools for preliminary and conceptual design only capture design specifications. In contrast, designers and manufacturing engineers need to develop and evaluate alternative designs and plans.

Thus, integrating design and planning raises numerous issues that need investigation: integrating electrical and mechanical design; representing design and process options that occur at different levels; generating feasible design and process options; evaluating feasible alternatives; comparing feasible alternatives on multiple criteria; and providing seamless access to external data sources. Our efforts to integrate the design and planning of microwave modules addresses many of these issues. In this chapter, we describe three major research efforts.

The first research effort is a detailed process planning procedure for microwave modules. The procedure integrates electrical and mechanical computer-aided design (CAD). It uses knowledge about the relevant manufacturing processes and information from the CAD models to generate a detailed process plan and evaluate the product's manufacturability.

The second effort is a trade-off analysis model that represents the design and process options associated with a microwave module and supports the designer's need to select options and balance multiple criteria such as cost, yield, and time.

The third research effort is a generative high-level process planning approach for partner selection and synthesis of virtual enterprises. The designer uses an object-oriented group technology scheme to represent the product design. Manufacturing resource models describe the manufacturing process capabilities and performance of potential partners. The generative high-level process planning methodology identifies feasible process planning and alternatives; represents them using a structured decision tree; estimates each alternative's total cost, quality, and cycle time; and allows the designer to select the most suitable one.

The remainder of the chapter is structured as follows: Section 14.2 describes the detailed process planning approach. Section 14.3 describes the electromechanical assembly model. Section 14.4 summarizes the high-level process planning approach. Section 14.5 discusses the issues that the previous research addresses and considers future research directions.

14.2 CAD INTEGRATION AND DETAILED PROCESS PLANNING

The detailed process planning approach forms the Electromechanical Design and Planning System (EDAPS), a toolkit for microwave module manufacture that integrates electronic and mechanical computer-aided design, electronic and mechanical process planning, and plan-based design evaluation.[16] The system generates process plans concurrently with the design and assists the designer in performing plan-based critiquing of microwave module designs. Process planning occurs both in the mechanical domain, including such processes as drilling and milling, and in the electronic domain, including such processes as through-hole plating, artwork deposition, placing components, and soldering. This provides feedback about manufacturability, cost, and cycle time to the designers, based on process plans for the manufacture of the device.

This research explores many issues related to integrated design and planning: integrating electrical and mechanical design, representing process options at different levels, generating feasible process options, evaluating feasible alternatives using multiple metrics, and providing seamless access to different modules and multiple data sources.

The detailed process planning approach includes CAD tools for electronic and mechanical design and an integrated process planner for mechanical and electronic manufacturing processes. The architecture of the corresponding system is shown in Figure 14.4 and contains three related modules:

- In the circuit schematic and circuit layout module, the designer generates electronic circuitry. An integrated set of commercial software supplied by EEsof's Series IV system[13] forms the core of this module. On top of this software, we have built routines that provide application-specific information. We address the circuit layout module in more detail in Section 14.2.1.
- In the substrate design module, the designer performs mechanical feature-based design. Bentley Systems' Microstation CAD software[24] supplies the set of tools required to achieve this functionality. Custom routines in C++ and the Microstation Development Language build the appropriate features, integrate Microstation with the rest of the system, and extract and supply relevant manufacturing information to individual modules. We address the substrate design module in more detail in Section 14.2.2.
- In the process planning and plan evaluation module, the AI-based process planner creates a process plan for the design and reports to the designer the cost and cycle time for the design. We describe the process planning and plan evaluation module in more detail in Section 14.2.3.

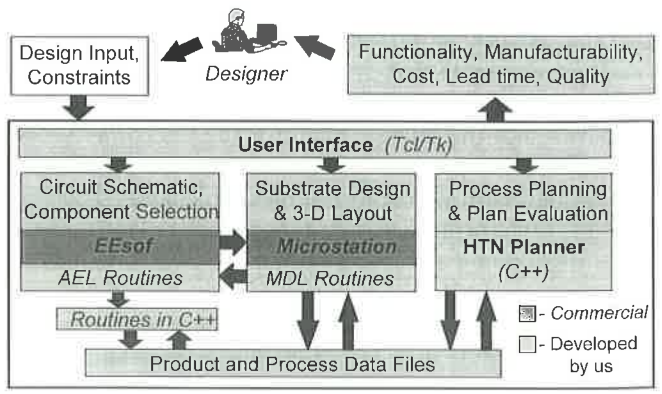

Figure 14.4 EDAPS system architecture.

The coordination of these modules and the exchange of data among them take place through a user interface written in the Tcl/Tk language.[25] This user interface allows the designer to smoothly interact with the heterogeneous modules that constitute the system.

14.2.1 Circuit Schematic and Circuit Layout Module

The microwave circuit design and layout module uses a powerful set of tools included in the EEsof electronic CAD tool. In particular, the module uses EEsof's Libra tool for linear and nonlinear schematic circuit design and EEsof's ACADEMY tool for layout generation.

Using Libra, the designer designs the "schematic circuit," choosing components from predefined and user-defined device libraries. In schematic circuits, the components and transmission lines are represented as symbols. The actual artwork shapes corresponding to the circuit elements are not represented in the schematic. The designer subjects this circuit to time and frequency domain response analyses to achieve the desirable functionality. The designer does several design iterations, and Libra evaluates each design until the designer obtains a functionally satisfactory circuit.

Libra incorporates some design-for-manufacturing principles. Based on the required circuit functionality, the limiting tolerances on each component's electrical parameters can be calculated and thus manufacturing yield can be predicted. Yield information calculated this way gives an idea of the required investment in postproduction. This yield metric is the maximum yield that can be expected out of the design. It is useful in performing sensitivity analysis of the design. However, manufacturing yields are not only a function of electrical parameter tolerances. Some of the other influences can be the defects that result from the soldering processes that are directly related to the package shape, dimensions, and materials.

Once the schematic circuit is complete, the artwork shapes necessary to realize circuit interconnections and other metallizations on the substrate are automatically generated by ACADEMY. The layout can also be interactively laid down to fit the artwork within specified size constraints and to incorporate those artwork layer elements that do not have electronic significance. Examples of such elements are product identification numbers, design version numbers, fiducial marks, and the global origin for the microwave module.

In order to develop mechanical features, this module converts layout data into the IGES format[20] for export to the mechanical CAD system described in Section 14.2.2.

14.2.2 Substrate Design Module

The substrate design module uses Microstation, a comprehensive CAD package supplied by Bentley Systems Inc. The Microstation modeler is a parametric feature-based design system. According to Salomons,[29] features are information sets that refer to aspects of form and other attributes of a part, such that these sets can be used in reasoning about the design, performance, or manufacture of the part or assemblies they constitute. The ACIS solid modeler[1] is used internally to represent and provide methods to generate and modify features defined in Microstation. In this approach, the following manufacturing features are most relevant to process planning and plan evaluation:

- *Dielectric.* The dielectric substrate is assumed to have prismatic geometry with designer-specified corner radii, thereby directly corresponding to the material removal shape volumes of end-milling features. The feature information set contains dimensions, corner radii, location, orientation, and electronic parameters such as the dielectric constant and dielectric material.
- *Heat Sink.* The initial geometry of the heat sink (or ground plane) is also assumed to be prismatic with corner radii. Related information describes its material, length, width, height, and corner radius. An additional constraint specifies that the widths and lengths of the heat sink and dielectric be equal, because the dielectric is fabricated on the heat sink.
- *Component Mounting Pockets.* For packaged components that require recesses in the substrate and heat sink for mounting and grounding, component mounting pocket features whose geometry corresponds to an end-milling feature have been provided. By default, the dimensions of such a feature are a function of the dimensions of the packaged component, and its location is the same as that of the packaged component. This generic end-milling feature can be used to construct all other cutouts, pockets, and grooves in the dielectric and heat sink.
- *Vias.* Conductive through-holes (vias) are represented as manufacturing features because they directly correspond to the material removal volumes of drilling features. In addition to the diameter, location, orientation, and length of the holes, the via feature stores useful manufacturing information such as electroplating thickness, if electroplated, and, if tapped, a reference to the pitch, nominal diameter, and the owner screw.

14.2.3 Process Planning and Plan Evaluation Module

To perform detailed process planning for microwave module designs, we use an approach from artificial intelligence called *hierarchical task network* (HTN) planning.[11,28,32,34] We have also used this approach in some of our other work.[31]

Hierarchical task network planning proceeds by taking a complex task to be performed and considering alternate methods for accomplishing the task. Each method provides a way to decompose the task into a set of smaller tasks. By applying other methods to decompose these tasks into even smaller tasks, the planner will eventually produce a set of primitive tasks that it can perform directly.

As an example, one method for making the artwork is to perform the following series of tasks: precleaning for the artwork, followed by application of photoresist, followed by photolithography for the artwork, followed by etching. There are several alternate methods for applying photoresist: spindling the photoresist, spraying on the photoresist, painting on the photoresist, and spreading out the photoresist from a spinner. The relationships between tasks and methods form a task network, part of which is shown in Figure 14.5.

This decomposition of tasks into various subtasks is important for process planning for the manufacture of microwave modules for two reasons. First, the decomposition in an HTN naturally corresponds to the decomposition of a design into the parts and processes required to manufacture it. Second, the ability to include the complex tasks "make drilling and milling features," "make artwork," "assembly and soldering," and "testing and inspection" in sequence provides a uniform framework that can naturally accommodate all the processes in mechanical and electronic manufacturing.

This decomposition requires manufacturing knowledge. Sometimes a particular method can always be used to perform a particular task. For example, because spreading out the photoresist from a spinner is so accurate, this method can always be used to perform the task of applying the photoresist. Sometimes a particular method can only occasionally be used to perform a particular task. For example, because spraying on the photoresist is only somewhat accurate, this method cannot be used to apply the photoresist if a coupler in the artwork has a gap less than or equal to 10 mils.

Certain tasks are primitive, meaning that they do not break down into any other tasks. We consider a task to be primitive if it is considered to be a single small step in the manufacturing process. For example, precleaning for the artwork is a primitive task. Once the complex task of making the entire product has been broken down into a series of primitive tasks, a process plan has been created; carrying out the steps of the process plan will manufacture the product.

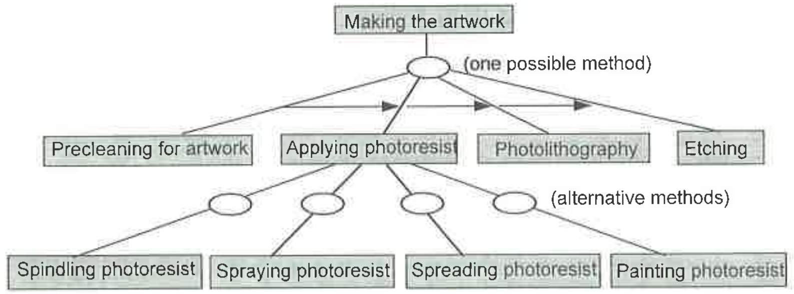

Figure 14.5 Part of the task network for microwave module manufacture.

Consider the substrate shown in Figure 14.6. "Make board" decomposes into "Make plated through-holes and features," "Make artwork," "Assembly," and "Testing and inspection." "Make plated through-holes and features" decomposes into "Drill plated through-holes," "Plate plated through-holes," and "Make features." "Drill plated through-holes" and "Plate plated through-holes" decompose into primitive tasks, which we do not discuss here.

"Make features" is the next task, and because there are features left to be made, it decomposes into "Make a single feature" and "Make features." This "loop" in the task network allows us to decompose a task, such as "Make features," into zero or more subtasks, such as "Make a single feature."

"Make a single feature" decomposes into "Setup and end-mill (the top cutout on the left-hand side of the substrate)," because, in our planner, we always do all the milling before we do any drilling. "Setup and end-mill (the top cutout on the left-hand side of the substrate)" decomposes into "Setup," "Setup end-milling tool," and "End-mill." Because the part is not currently set up on the machining center, "Setup" decomposes into "Orient the part," "Clamp the part," and "Establish a datum point." All three of these tasks are primitive.

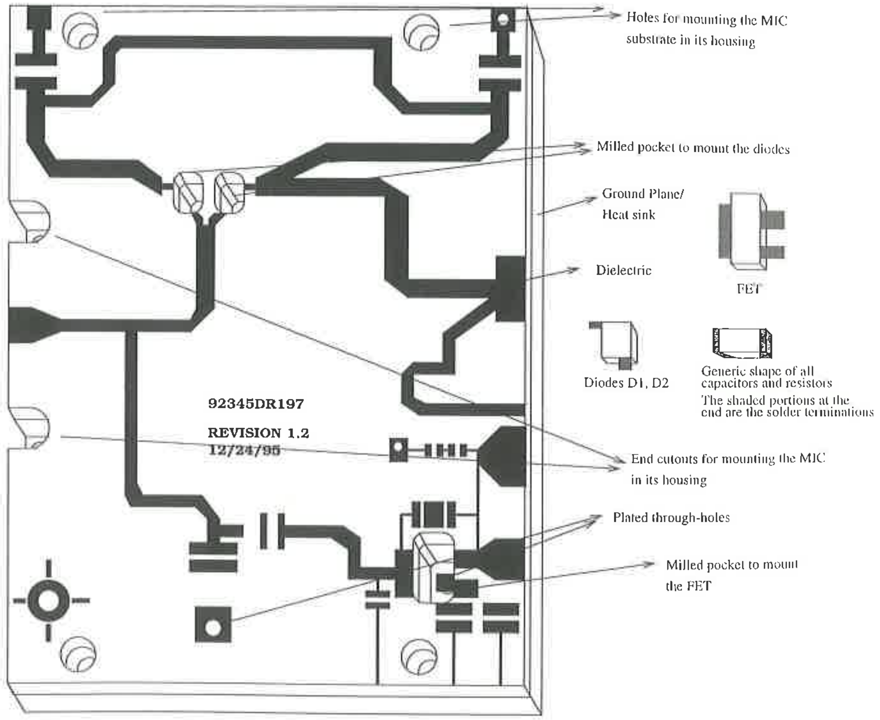

Figure 14.6 Development of mechanical features on the Mixer-IF amplifier substrate.

"Setup end-milling tool" is the next task, and, because we just started, we assume that the correct end-milling tool is not installed on the machining center. Thus, this task decomposes into "Install end-milling tool (of the appropriate size)," which is a primitive task. Assuming tight tolerances, "End-mill" decomposes into "Rough end-mill" and "Finish end-mill," both of which are primitive tasks.

"Make features" continues to decompose until a plan has been created for all five milling features and all thirteen drilling features. The next complex task is "Make artwork."

"Make artwork" decomposes into "Preclean for artwork," "Apply photoresist," "Artwork photolithography," and "Etching." In our planner, all of these tasks but "Apply photoresist" are primitive. "Apply photoresist" has several alternate methods: "Spread photoresist from a spinner" or "Spindling the photoresist" or "Spraying the photoresist." "Painting on the photoresist" is not a feasible alternative in this case because painting on the photoresist is not accurate enough for this substrate.

The rest of the plan is generated in a similar manner, and output is provided in the format shown in Figure 14.7. The output of the detailed process planner includes:

- A totally ordered sequence of process specifications that can be used to produce the finished substrate from the materials given.
- Process parameters of all the processes that are required to manufacture the device.
- Estimates of cost and cycle times.

The output can be fed back to the designers, with cycle time "hot spots" indicated. The designer can then choose to change the design elements, in order to reduce the cycle time.

When the designers and manufacturing engineers are satisfied with the design, the artwork elements will be extracted out of Microstation, and the equivalent IGES file will be generated and sent to ACADEMY. ACADEMY can then export the design file in either IGES format or Gerber format for manufacturing.

As mentioned before, because the method of application of photoresist does not affect anything else in the plan, the planner will locally decide which photoresist application method is cheapest in this instance—"Spindling the photoresist," let us say—keep only that subtask in the plan, and ignore the remainder.

The planning module constructs a set of process plans and evaluates them to see which takes the least amount of time. In some cases, it evaluates a set of incomplete process plans and discards all but the one which takes the least amount of time. For example, because the method of application for photoresist does not affect the method of application for solder paste, if the quickest method of applying photoresist is spraying it on, then there is no need to generate process plans in which some other method of application is used. If no process plans can manufacture the device—because some manufacturability constraint, such as achievable tolerance, is violated—the planner reports the failure and the reason for the failure to the designers.

```
Parts:
Block
 Dimensions: 7,4,1
 Ground material: Aluminum
 Substrate: Teflon
 Substrate thickness: 30 mils
 Metallized layer: Copper
 Metallized layer thickness: 7 mils
 Part number: 80280SA/2
Resistor
 Name: P1
 Part number: RNC55H2370FS
 Description: Motorola SS163
 Specification: MIL-R-55182
[...]
Processes:
Opn A  BC/WW  Setup  Run   LN  Description
001 A   VMC1    2.0  0.0   01  Hold substrate with
                               flat vise jaws at
                               3.5,4,0.5 and
                               3.5,0,0.5
                           02  Establish datum point
                               at 0,0,1
001 B   VMC1    0.0  0.6   01  Drill hole: 1,4,0
                               depth: 1 using
                               0.25 radius bit
                           02  Drill hole: 3,4,0
                               depth: 1 using
                               0.25 radius bit
001 C   VMC1    0.0  0.3   01  Drill hole: 3.5,6.5,0
                               depth: 1 using
                               0.125 radius bit
001 D   VMC1    0.0  5.0   01  Mill slot: 0.5,1,0
                               dimensions 3,1,1
                               using 0.5 radius
                               end-milling tool
001 T   VMC1    2.0  5.9   01  Total time on VMC1
```

Figure 14.7 Part of a process plan in a standard format.

"Setup end-milling tool" is the next task, and, because we just started, we assume that the correct end-milling tool is not installed on the machining center. Thus, this task decomposes into "Install end-milling tool (of the appropriate size)," which is a primitive task. Assuming tight tolerances, "End-mill" decomposes into "Rough end-mill" and "Finish end-mill," both of which are primitive tasks.

"Make features" continues to decompose until a plan has been created for all five milling features and all thirteen drilling features. The next complex task is "Make artwork."

"Make artwork" decomposes into "Preclean for artwork," "Apply photoresist," "Artwork photolithography," and "Etching." In our planner, all of these tasks but "Apply photoresist" are primitive. "Apply photoresist" has several alternate methods: "Spread photoresist from a spinner" or "Spindling the photoresist" or "Spraying the photoresist." "Painting on the photoresist" is not a feasible alternative in this case because painting on the photoresist is not accurate enough for this substrate.

The rest of the plan is generated in a similar manner, and output is provided in the format shown in Figure 14.7. The output of the detailed process planner includes:

- A totally ordered sequence of process specifications that can be used to produce the finished substrate from the materials given.
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The output can be fed back to the designers, with cycle time "hot spots" indicated. The designer can then choose to change the design elements, in order to reduce the cycle time.

When the designers and manufacturing engineers are satisfied with the design, the artwork elements will be extracted out of Microstation, and the equivalent IGES file will be generated and sent to ACADEMY. ACADEMY can then export the design file in either IGES format or Gerber format for manufacturing.

As mentioned before, because the method of application of photoresist does not affect anything else in the plan, the planner will locally decide which photoresist application method is cheapest in this instance—"Spindling the photoresist," let us say—keep only that subtask in the plan, and ignore the remainder.

The planning module constructs a set of process plans and evaluates them to see which takes the least amount of time. In some cases, it evaluates a set of incomplete process plans and discards all but the one which takes the least amount of time. For example, because the method of application for photoresist does not affect the method of application for solder paste, if the quickest method of applying photoresist is spraying it on, then there is no need to generate process plans in which some other method of application is used. If no process plans can manufacture the device—because some manufacturability constraint, such as achievable tolerance, is violated—the planner reports the failure and the reason for the failure to the designers.

```
Parts:
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 Metallized layer thickness: 7 mils
 Part number: 80280SA/2
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 Name: P1
 Part number: RNC55H2370FS
 Description: Motorola SS163
 Specification: MIL-R-55182
[...]
Processes:
Opn A  BC/WW  Setup  Run   LN  Description
001 A   VMC1    2.0  0.0   01  Hold substrate with
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                               3.5,4,0.5 and
                               3.5,0,0.5
                           02  Establish datum point
                               at 0,0,1
001 B   VMC1    0.0  0.6   01  Drill hole: 1,4,0
                               depth: 1 using
                               0.25 radius bit
                           02  Drill hole: 3,4,0
                               depth: 1 using
                               0.25 radius bit
001 C   VMC1    0.0  0.3   01  Drill hole: 3.5,6.5,0
                               depth: 1 using
                               0.125 radius bit
001 D   VMC1    0.0  5.0   01  Mill slot: 0.5,1,0
                               dimensions 3,1,1
                               using 0.5 radius
                               end-milling tool
001 T   VMC1    2.0  5.9   01  Total time on VMC1
```

Figure 14.7 Part of a process plan in a standard format.

14.3 TRADE-OFF ANALYSIS MODEL

The second research effort explores in more detail the trade-off issues faced during the microwave module design. It proposes a trade-off analysis model and the associated procedure that allows the designer to choose sets of alternate parts and processes that are desirable with respect to a set of metrics. This research explores multiple issues related to integrated design and planning: representing design and planning options and comparing feasible alternatives on multiple criteria.

The trade-off is performed with respect to five metrics: cost, manufacturing yield, number of suppliers, supplier lead time, and quantity discounts. The problem is formulated as a multiobjective integer program that the designer iteratively solves to search for and sort desirable solutions, as described in the following discussion.

The modeling approach exploits the following assumptions: The conceptual design for the microwave module (board) is given and is to be realized as a single assembly. The design specifies the set of required generic component types and, for each such component type, a number of specific alternatives. For each specific component, there is a list of processes that are related to the component and the alternatives (if any) for each such process. This defines an and–or tree that captures the structure of the design. Key attributes such as material costs, run times, setup times, and defect rates are known for components, processes, and component–process combinations. In addition, the supplier's lead time and the supplier's quantity discount structure are known for each component. The designer's problem is to determine a set of components (and thus suppliers) and processes that are "efficient" with respect to the five objectives mentioned earlier.

The model uses the following notation:

m = number of generic components required
P_i = generic component i, $i = 1, \ldots, m$
n = number of alternate components available
$V = \{p_1, \ldots, p_n\}$, the set of available components
V_i = alternate components for generic component P_i, $V_i \subset V$
s_j = number of generic processes required for p_j
Q_{jk} = generic process k for component p_j, $k = 1, \ldots, s_j$
r = number of alternate processes available
$W = \{q_1, \ldots, q_r\}$, the set of available processes
W_{jk} = alternate processes for generic process Q_{jk}, $W_{jk} \subset W$

The decision variables are x_j, $j = 1, \ldots, n$, and y_t, $t = 1, \ldots, r$. $x_j = 1$ if component p_j is selected and 0 otherwise. $y_t = 1$ if process q_t is used in the assembly and 0 otherwise.

The following constraints define the and–or structure of the model:

$$\sum_{p_j \in V_i} x_j = 1 \qquad \text{for all } i = 1, \ldots, m$$

$$\sum_{q_t \in W_{jk}} y_t = x_j \qquad \text{for all } j = 1, \ldots, n,\ k = 1, \ldots, s_j$$

The first set of constraints represents the design requirements: The design must contain generic components $P_1, P_2, \ldots, P_m$. Similarly, the second set of constraints represents the requirements of component p_j (if p_j is a selected component): p_j requires generic processes $Q_{j1}, Q_{j2}, \ldots, Q_{js_j}$. Each set V_i represents the design options: Generic component P_i requires p_1 or p_2, if both are elements of V_i. Similarly, set W_{jk} represents the process options: Generic process Q_{jk} requires q_1 or q_2, if both are elements of W_{jk}.

The model includes additional parameters and constraints necessary to measure the five objective functions, which are normalized with respect to designer-supplied limits (lower and upper bounds) and combined using designer-specified weights. In addition, feasible solutions must satisfy all of the upper bounds; thus, these upper bounds define the search space. The resulting integer program resembles an uncapacitated facility location problem, which is well structured and can be solved using the linear programming tool CPLEX[10] with reasonable computational effort.

After specifying the model parameters, the designer iteratively solves the trade-off analysis model to generate a set of designs that are "efficient" with respect to the five metrics mentioned earlier. The designer specifies, for each objective function, upper bounds and weights. The bounds limit the search space, and the optimization tool sorts the feasible solutions by their weighted performance and outputs the best solution(s). From this feedback, the designer changes the bounds to expand or contract the search space or changes the relative weights to find other good solutions in the search space. This continues until the designer has located the most desirable solutions.

14.4 PARTNER SELECTION FOR MICROWAVE MODULE MANUFACTURING

Our third effort in the area of microwave module design and planning addresses selecting partners for the joint manufacture of a new microwave module design. Specifically, we present an approach that, given a new microwave module design, generates feasible process and partner alternatives, evaluates the feasible alternatives, allows the designer to search for and sort these alternatives on multiple criteria, and selects the most efficient set of partners.

Section 14.4.1 presents an overview of the design evaluation and partner selection methods and system. Section 14.4.2 describes the necessary information models. Section 14.4.3 describes high-level process planning, the method that generates process and partner alternatives. Section 14.4.4 describes evaluating the alternatives, and Section 14.4.5 describes selecting an efficient partnership.

14.4.1 Overview

Figure 14.8 illustrates our approach. The output of the designer's CAD system is translated and stored in an integrated product model. This model uses the data definitions of STEP, the international Standard for the Exchange of Product Data (ISO 10303[21]), and thus supports the free exchange of data between the firm and its partners.

Design evaluation requires more abstract product information than that in the STEP-based product model. Concise group technology (GT) codes are used to search for and retrieve similar products, and high-level generative process planning uses some detailed data about those product attributes that the GT code includes. This information forms the object-oriented group technology (OOGT) product model. We have developed (and implemented as the Group Technology Design Processor in Fig. 14.8) algorithms that derive the OOGT product model from the STEP-based product representation. In the design retrieval step (the product search module), the designer exploits the concise nature of the GT codes to search quickly for similar products in the product databases of candidate partners.[22]

To generate and evaluate partnering alternatives, we use a high-level process planning approach. In the first step of this approach, the feasibility assessment module generates feasible manufacturing alternatives. The system uses generic data about manufacturing processes and specific information about the process capabilities of the candidate partners to construct feasible plant-specific process plans and identify features of the design that are infeasible with respect to generic or partner-specific process capabilities. The feasible process plans specify the sequence of manufacturing operations, the candidate partners who could perform these operations, and the design attributes to be realized at each operation. (Unlike the approach presented in Section 14.2, the process plans do not describe process details, process parameters, tooling, fixtures, or other specific manufacturing instructions necessary for actual production.) For infeasible processes, this step identifies for the designer the related attributes that need revision.

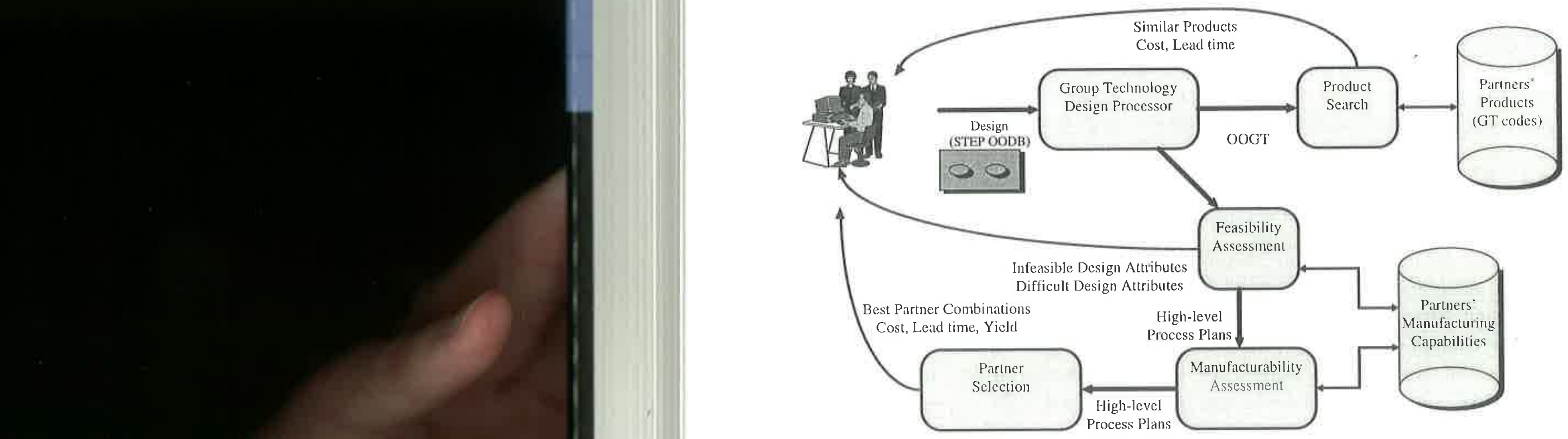

Figure 14.8 Design evaluation and partner selection approach.

The manufacturability assessment module, which uses generic data about manufacturing processes and specific performance measures about the processes of the candidate partners, evaluates each feasible process and partner combination with respect to cost, quality, and cycle time. In addition, in this step the designer can determine those attributes that most affect the design's cost, quality, and cycle time. With this information, the designer can initiate redesigns that improve the product's performance within the given set of processes and partners.

Once the design evaluation is complete, the system allows the designer to sort the alternative high-level process plans on selected criteria, identify the partners that form the most desirable plan, and receive feedback on the plan's expected cost, quality, and cycle time.

Note that Figure 14.8 illustrates the entire design evaluation and partner selection system. This section describes only the portions that generate, evaluate, and compare process planning alternatives. The high-level process planning approach consists of the feasibility assessment and manufacturability assessment modules. The partner selection module allows the designer to compare alternatives and select the one that is most suitable on multiple criteria.

14.4.2 Information Models

The partner selection approach requires three general types of data: product design data, manufacturing process data, and manufacturing resource data. We identify and manage the necessary data by constructing appropriate information models (see Candadai et al.[4] for a complete description).

Product Information As described previously, the designer initially stores a product design in an integrated product model that uses STEP to support the free exchange of data between the firm and its partners. Design evaluation requires more abstract product information, however. The product information required for high-level process planning is captured in the object-oriented group technology (OOGT) product model[5, 16] shown in Figure 14.9. This model is a concise view of a product design. It stores critical design information more compactly and at a different level of abstraction than the complete product model.

The top level of this information model describes general product attributes including part number, raw material, and production quantity. The lower levels capture information about both mechanical and electrical product attributes. The mechanical information describes the product envelope in terms of enveloping faces and the product features in terms of parametric attributes such as feature volume, corner radii, minimum tolerance, and surface finish. Additional feature-related information includes thin sections, sections with abrupt thickness changes, and directions along which a feature causes an undercut. The electrical information describes the electrical product design requirements including artwork layout and tolerances, component types and mounting specifications, and soldered and nonsoldered hardware requirements.

Process Information The generic process knowledge used in this approach is organized in a simple process information model. This information, typically found in manufacturing handbooks, describes universal process capabilities, material–process compatibilities, and recommended production quantities. Table 14.1 shows a representative table from the generic process information model, which was populated with data from various sources including design handbooks,[2, 8, 30] manufacturing handbooks,[9, 12, 17, 35] and materials handbooks.[14] It shows the compatible material–process combinations, compatible feature–process combinations, and some global process capabilities such as the feasible design quantity range.

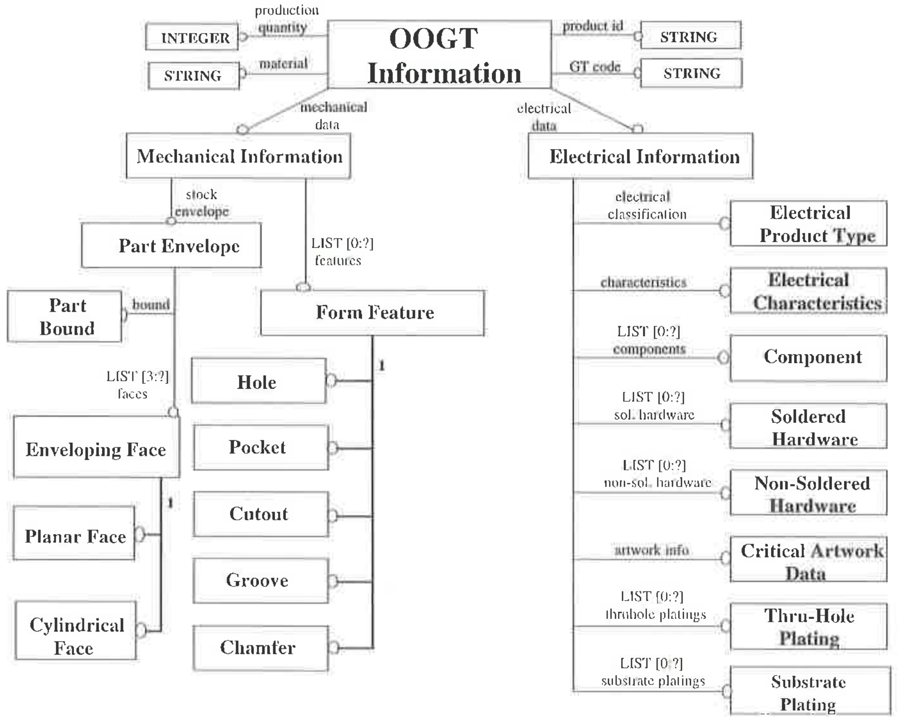

Figure 14.9 OOGT product model.

Manufacturing Resource Information The manufacturing resource model includes general information about a corporation and its manufacturing facilities (plants) and also detailed data about the systems in each plant. Most important to process planning and manufacturability analysis are the data that describe the capabilities and performance of a plant's manufacturing processes and the associated resources. Information about process availability and process capabilities (such as maximum envelope size and achievable accuracy of a milling process) are used to generate the plant-specific process plans (as discussed in Section 14.4.3). The performance measures (including cost rates, queue time, capacity, process variance, and yield) is used to evaluate the plans (Section 14.4.4). Additional details are given by Candadai et al.[4]

14.4.3 Generating Partnering Alternatives: High-Level Process Planning

Supporting the high-level process planning approach, which generates feasible partnering alternatives, is a process planning data structure (PPDS) that captures information about the various process alternatives, their sequence, and the plants that perform these processes.[23]

The PPDS structure reflects the processes used to manufacture microwave modules and discussed in Section 14.2: drilling and plating conductive through-holes (vias), machining the microwave module substrate features, generating artwork (substrate etching and plating), automated or manual component assembly and soldering, and testing. (Although the same principles apply, a different product's PPDS would include a different set of processes. For example, a strictly mechanical product would include primary, secondary, and tertiary processes.) As shown in Figure 14.10, the PPDS has alternating levels of process and plant options, which represent the processes and plants that may be used to manufacture the product. The combination of a process option and a plant option represents a complete processing step in a high-level process plan: It describes the operations performed at the manufacturing plant and the remaining features that need to be manufactured at subsequent steps. A high-level process planning alternative is a sequence of process–plant combinations.

High-level process planning uses the OOGT product model to obtain critical design attributes, the process information model to relate design attributes to manufacturing processes, and the manufacturing resource model to identify the potential partners' specific manufacturing capabilities.

The approach constructs the PPDS by selecting feasible process and plant alternatives at each step.[15] Process selection is a plant-independent procedure that retrieves all candidate processes (from the process database) associated with key design attributes and discards processes that are globally infeasible (i.e., infeasible at any plant). All required subprocesses must be feasible in order for a process to be feasible. If the design has plated through-holes, the PPDS includes two processing alternatives: One corresponds to machining and then plating; the second corresponds to through-hole plating and then machining the remaining features. The assembly process (manual or automatic) depends on the component mounting methods and the production quantity.

Plant selection uses process capability information from the manufacturing resource model to identify the candidate partners that can perform the process (or all required subprocesses) to generate the corresponding attributes of the product design. For example, a plant's plating process must be able to plate the required thickness, and the etching process must be able to achieve the required line width tolerance and line spacing tolerance. If a process or plant option is infeasible, the process planning approach identifies the reason and lists it in the PPDS, which may allow the designer to modify the product design appropriately.

Each path through the resulting PPDS corresponds to a feasible high-level process plan (a sequence of feasible process–plant combinations with no remaining features) or ends in an infeasible option.

14.4.4 Evaluating Feasible Process Plans

After the feasibility assessment module generates the PPDS, the manufacturability assessment procedure evaluates the cost, quality, and cycle time of each feasible process–plant combination.[18, 23] The procedure uses process-specific knowledge, expressed as rules and formulas, and the potential partners' process performance data, which the manufacturing resource model describes.

The cycle time associated with each process is the queue time for the process, the setup time for the entire production quantity and each batch, and the total run time of all subprocesses. For example, the milling setup time is the total recurring setup time (for loading, unloading, and cleaning) and the nonrecurring setup time. The milling run time includes the actual cutting time for all features (roughing and finishing) and the tool approach time (during rapid and slow travel). The total etching time includes the photoresist masking time, the photoresist exposure time, the etching time, and the photoresist stripping time. The manufacturing resource model provides the plant-dependent queue time. Process-specific procedures calculate the process setup and run times based on design characteristics, plant capabilities, and process knowledge. The approach includes procedures for milling, drilling, plating, etching, automated assembly, automated soldering, manual assembly, and testing. (We have also developed procedures for other mechanical processes: sand casting, investment casting, forging, surface grinding, and internal grinding.)

The cost of the process is the setup cost and direct labor cost of the process. The costs are the plant-specific setup and labor rates multiplied by the setup and run times and a plant-specific overhead rate. The quality of a process is the process capability ratio C_p (where appropriate) and a plant-specific yield otherwise. The C_p for etching is the quotient of the minimum artwork tolerance (the minimum of the line width tolerance and the line spacing tolerance) and six times the plant's etching standard deviation. If a process consists of subprocess, the procedure determines the performance of each subprocesses and aggregates them to calculate the process performance. (In this casé, C_p's are converted to yields, multiplied, and transformed again to a composite C_p.) When this step is completed, the PPDS contains the feasible processes and plants and the cost, quality, and cycle time of each combination, which is required for the comparison of high-level process plans and selection of partners.

14.4.5 Partner Selection

The partner selection approach allows the designer to compare the different high-level process plans. Partner selection follows the generation and evaluation of high-level process plans, as described previously.

An explicit enumeration technique constructs all feasible high-level process plans from the feasible process–plant pairs in the PPDS. Each feasible alternative is evaluated with respect to cost, quality, cycle time, and the transportation cost between consecutive plants in the process plan. These performance measures combine the cost, quality, and cycle time for the plan's component process–plant pairs. The transportation cost depends on the location of the candidate manufacturing plants.

The designer may search for desirable alternatives by excluding those alternatives that are dominated by some other alternative with respect to any combination of criteria and by excluding those alternatives that are inferior with respect to user-specified thresholds for one or more criteria. The designer can sort the remaining alternatives on a linear combination of some criteria. The designer provides a weight for each performance criterion, and the weighted combination of the criteria forms the new performance criterion. For example, these weights allow the designer to convert all criteria to dollars or to give relative weights to the criteria.

In addition, the designer can specify preferences in the form of natural language expressions about the importance of each performance attribute (cost, quality, cycle time). Using a fuzzy extension of the analytic hierarchy process (fuzzy-AHP),[26, 27] the partner selection approach combines these preferences with existing data (from industrial surveys and statistical analysis) to reemphasize attribute priorities. These redefined attribute priorities reflect the specific needs of the firm for this product. In the fuzzy-AHP procedure, the pairwise comparisons in the judgment matrix are fuzzy numbers that are modified by the designer's emphasis. Using fuzzy arithmetic and alpha cuts, the procedure calculates a sequence of weight vectors that will be used to combine the process plan's scores on each attribute. The procedure calculates a corresponding set of scores and determines one composite score that is the average of these fuzzy scores.

14.5 CONCLUSIONS

This chapter identifies the issues related to the integrated design and process planning of microwave modules. In addition, this chapter discusses three related research efforts that explore these issues: detailed process planning, trade-off analysis, and high-level process planning. We anticipate that our methods and results provide significant insight into concurrent engineering of other electromechanical systems. In this section, we review the specific contributions of our research efforts and discuss promising research directions.

Integrating Electrical and Mechanical Design The ultimate solution to the problem of integrating electronic and mechanical design can be found in one of at least two ways. One possibility is the implementation of a single monolithic software system that includes both an electronic design subsystem and a solid modeling engine for mechanical design. The data structures in such an implementation would relate the solid model of each shape element in the mechanical design with its function in the schematic of the electronic design. Such a solution would allow tightly coupled interaction between the electronic design subsystem and the mechanical design subsystem—and could be used to generate sophisticated feedback to the designer, such as suggestions for how to change the proposed design to improve its manufacturability while maintaining acceptable performance. Unfortunately, such an approach requires the creation of a completely new system, which may be incompatible with the legacy systems already used in practice.

Another possibility—the approach we have taken in the detailed process planning research—is to integrate existing systems for electrical and mechanical design. In addition, this approach requires extending the electronic design system to keep track of some of the information needed for mechanical design so that this information will not be lost when users change the electrical design, and similarly extending the mechanical design system. The disadvantage of such a solution is that it may limit the interaction between the electronic design system and the solid modeler and that, in any case, translating and transferring information from one system to another takes time and work. (In our system, because our feedback is based on the process plan for manufacturing, we did not have to translate much information back to the electronic design system from the solid modeler.) However, such a solution allows companies to keep legacy systems in place; in addition, designers can change their electronic design system without changing their solid modeler or vice versa.

Representing and Analyzing Design and Planning Options In an integrated design and planning environment, a designer needs to represent and analyze alternate design and planning options at multiple levels of detail. These options include alternate components, suppliers, manufacturing processes, and manufacturing partners. Our research explores different structures for representing these alternatives.

The trade-off analysis model specifies the set of required generic component types and, for each component type, a number of specific component alternatives. For each specific component is a list of processes that need to be performed on the component and the alternatives (if any) for each such process. This defines the basic and–or tree that captures the structure of the design.

The high-level process planning approach includes a process planning data structure (the PPDS) that captures information about the various process alternatives, their sequence, and the plants that perform these processes. Each path through the PPDS corresponds to a feasible high-level process plan or ends in an infeasible alternative. The combination of a feasible process option and a feasible plant option represents a complete processing step in a high-level process plan. A feasible high-level process plan is a sequence of feasible process–plant combinations.

Our detailed process planning procedure uses an approach from artificial intelligence called hierarchical task network (HTN) planning, which proceeds by taking a complex task to be performed and considering alternate methods for accomplishing the task. Each method provides a way to decompose the task into a set of smaller tasks. By applying other methods to decompose these tasks into even smaller tasks, the planner will eventually produce a set of primitive tasks that it can perform directly.

The trade-off analysis model's and–or tree provides a very general way to describe design and planning requirements and the associated alternatives. The PPDS uses a version of this structure to describe high-level process planning and partnering alternatives. The HTN approach, which uses methods and tasks to explore a search space that has the and–or tree structure, specifies process sequences and allows a more general process decomposition. Although externally different because they support different types of decision making that occur at different times during the design life cycle, these data structures have the same hierarchical and–or structure. It seems clear that this structure supports design and planning during the evolution from conceptual design to preliminary design and detailed design. While refining the design, the designer identifies the additional requirements and alternatives associated with the design and planning alternatives chosen earlier.

Generating Feasible Design and Process Options In order to explore the complete search space and overcome the inertia that complex system design has (because the large number of required decisions limit the time available to develop new ideas), a designer requires tools that can generate, using a product design (at any level of detail) and appropriate manufacturing knowledge, feasible design and planning options and can identify the causes of infeasible options. Our research efforts include methods for identifying feasible manufacturing alternatives.

Most researchers have had great difficulty in developing generative process planners for complex mechanical parts, because their shape features may have complex interactions. However, generative process planning can be more easily applied to microwave modules, because the process plans use a relatively small set of operations and the mechanical features have fewer interactions.

During preliminary design, high-level process planning allows the designer to identify the most suitable processes and manufacturing facilities. The system uses generic data about manufacturing processes and specific information about the process capabilities of the candidate partners to construct feasible plant-specific process plans and identify features of the design that are infeasible with respect to generic or partner-specific process capabilities.

After the detailed design is complete, hierarchical task network planning appears to be an ideal approach for generating detailed process plans from the selected high-level process plan. The decomposition in an HTN naturally corresponds to the decomposition of a microwave module into the parts and processes required to manufacture it, and HTNs provide a unified framework that accommodates both electronic and mechanical manufacturing processes.

Evaluating Feasible Alternatives To choose the best options, a designer must know how each alternative performs. Our research explores different plan-based approaches for evaluating designs using multiple metrics. These approaches provide the designer with valuable feedback about the design during preliminary and conceptual design. This allows the designer to improve the design's manufacturability and avoid unnecessary iterations through the design and manufacturing cycle.

The detailed process planning approach estimates manufacturing cost and time based on the parameters of the required processes. The trade-off analysis model evaluates a design based on component–process combinations. The high-level process planning approach evaluates feasible process–partner combinations.

Comparing Feasible Alternatives on Multiple Criteria Faced with a large number of alternatives and the need to balance multiple criteria, a designer needs a convenient way to compare his or her performance and methods for making trade-offs according to specified criteria.

The trade-off analysis model and the partner selection approach provide tools that search for and sort alternatives (designs or process plans). In general, the designer first specifies thresholds to eliminate undesirable solutions and then weighs the different criteria to sort the remainder. An iterative approach allows the designer to change the thresholds and weights and therefore locate solutions that balance, subjectively at least, the various performance measures.

Providing Seamless Access to External Data Sources To generate and evaluate alternatives, integrated design and planning requires manufacturing knowledge that resides in a variety of sources (e.g., CAD models, parts catalogs, manufacturing process databases, and manufacturing resource models). Therefore, a designer needs seamless access to these sources so that their information can be retrieved and updated as needed. Our research identifies some required data sources and approaches for providing access to them.

The high-level process planning research described previously has identified some of the external data sources needed to support design and planning: product information models that describe the critical design information, relevant manufacturing process knowledge, the manufacturing resources' capabilities and performance (for each manufacturing facility or potential supplier), and a parts repository that has indexes for efficient searches.

Seamless access requires common data structures. The high-level process planning approach uses one data structure (the OOGT product model) to link the product design and process planning functions and another (the PPDS) to link the different modules that generate, evaluate, and compare the process planning alternatives. Similarly, the detailed process planner uses IGES files and a product information model to link the design and process planning modules.

In the detailed process planning system, a user interface written in the Tcl/Tk language provides seamless access. It allows the designer to smoothly interact with the heterogeneous modules that constitute the system.

Future Directions Although, as described previously, the research efforts described here explore many of the relevant issues and integrate portions of the design and manufacturing process, they are largely separate approaches, and one can clearly see that additional integration work remains. Our next research effort will integrate the trade-off analysis and detailed process planning approaches. The designer will generate an initial schematic based on device specifications and will simulate the schematic to test its functionality. In addition, the designer will specify the component types required. A high-level process planning procedure will determine the processes that the component types require and estimate the process performance. This provides the necessary input for the trade-off analysis model, and the designer will use this model to generate preliminary designs that are efficient with respect to multiple criteria. For each preliminary design, the designer will use electronic CAD tools to generate the artwork and mechanical CAD tools to create a solid model and add substrate features. Finally, the detailed process planner will generate and evaluate a complete process plan.

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Enabling Technologies for Automated Redesign

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Abstract

In this paper we identify AI technologies for enabling interactive automated redesign. We anticipate that these technologies can have great potential impact on future generations of intelligent CAD systems and methodologies.

1 Introduction

Computer-aided design (CAD) and CAD software is fast becoming a ubiquitous component of the modern manufacturing workplace. The decreasing costs of computational power has made sophisticated software for tasks such as finite element and mechanism analysis essential for increasing engineering quality and productivity. Software tools designed to reduce time-consuming build-test-redesign iterations are becoming crucial components for supporting concurrent engineering.

Many of these are tools for design analysis and critiquing. For example, they might examine whether a candidate design violates manufacturing or functional constraints (such as stress, acceleration, and so forth); or they might attempt to find possible suggestions to the user about how to improve a design [17, 14, 22, 5, 31]. Other analysis tools might include those that help the designer foresee potential problems with product life-cycle considerations such as performance, producibility, reliability, maintainability, and so forth.

In order to realize the advantages of collaborative engineering, these design analysis and critiquing systems must consider downstream manufacturing and life-cycle activities during the design phase. This has stretched the limits of traditional design activities and increased their complexity—presenting a variety of difficult computational problems.

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The automated redesign problem cuts across all of these issues and is of increasing interest to researchers, in both academia and industry. While some commercial software tools exist (such as those to reduce the number of parts in an assembly), satisfying solutions to the general redesign problem have eluded researchers. Existing systems vary significantly by approach, scope, and level of sophistication, with most attempting to capture manufacturability problems as collections of rules or heuristics. However, it has proven difficult to capture subtle manufacturability problems with hard-coded and coarse rules. Many problems can only be detected at the manufacturing planning level; problems that are compounded when multiple artifacts interact, not only in assemblies, but across the manufacturing enterprise. As a further complication, design is an interactive process and thus all of these computations must be handled in real-time.

This paper is written with several objectives in mind:

- to identify promising new AI technologies for enabling redesign and produce initial outlines for how they may be effectively applied to the real-world manufacturing problem;
- to help overcome two possible risks in the application of AI to computer-aided design: (1) that AI practitioners will apply their technologies to naive or unrealistically simplified versions of the real-world manufacturing problems or (2) that manufacturing engineers will apply the AI technologies in a manner that that does not fully exploit their strengths, ignores their computational costs, or overlooks their representational deficiencies.[1]

We anticipate that this work will serve to further the development of redesign systems by both expanding and improving the application of AI technologies to the problem; leading to the development of systematic methodologies for automated redesign. This will speed the introduction of automated designer's aides that capable of simultaneously considering design goals and manufacturing constraints, and identifying and alleviating manufacturing problems during the design stage.

2 Intelligent Automated Redesign

Many design problems are similar to design problems that have already been solved. Such problems can be approached by taking an existing design and modifying it, rather than producing a new design from scratch. There are several different types of redesign problems:

1. *Redesign for changes to functional specifications.* In many situations, the functional requirements a new design are minor variations on those of a previous design. One approach to solving this problem is to retrieve the old design and adapt it to fit the new requirements. An example of this kind of problem is redesigning a gear box housing to accommodate a larger gear.
2. *Redesign for manufacture with new processes.* The availability of new manufacturing processes introduces the need to redesign products to take advantage of them. For example, engine blocks traditionally were manufactured using casting followed by machining operations. But as die casting becomes a more economical process, the need for lighter cars is leading designers to contemplate the possibility of die-casted engine blocks. Although these engine blocks will have very similar functionality to what they had before, some redesign will be needed to adapt the old designs of engine blocks to the die casting process.
3. *Redesign for changing production resources.* The production resources for an organization change over time: new tools and technologies are added, production resources are prone to failure and downtime, etc. In an agile corporation, meeting the demands of the marketplace might require that products be redesigned to accommodate these changes.

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[1] For example, in the early 1980's rule-based expert systems were widely touted as panacea for use in producing solutions to many difficult real-world problems. Although expert systems were successful in some domains and are now in wide use (with several thousand successfully fielded systems), they were also applied to problems for which they were not well suited and produced poor results. The failure of these systems to deliver the results that were promised resulted in much wasted effort.

4. *Redesign for improved manufacturability, reliability, maintainability, etc.* In all component design procedures, the design goes through a design cycle consisting of analysis and review of the design. Now commonly referred to as *design for "X"* (DFX), where "X" can refer to cost effectiveness, quality, or other life cycle considerations such as reliability, maintainability, environmental impact, etc. Ideally, this design phase review should take into account can balance all of the production and performance constraints. This is not possible for all facets of the production process. For example, it is usually only after a component enters the production cycle that experienced process planners and machinists may discover that alterations in the design would be beneficial.

   A current goal is to develop stage tools for design phase analysis that can suggest design revisions, thus helping improve the design's ability to satisfy the constraints imposed by each "X." Our work toward the development of such a tool is described in [3].

This is a problem of increasing interest to researchers, in both academia and industry. For mechanical and electro-mechanical devices, it is much more difficult to reason about the many subtle interactions among the device requirements than it is for purely electrical devices. For example, changing the shape or size of a mechanical housing will change its strength and rigidity in ways that may be hard to predict without doing an extensive analysis (for example, using finite-element techniques).

While some commercial software tools exist (such as those to reduce the number of parts in an assembly), satisfying solutions to the general redesign problem have eluded researchers. Existing systems vary significantly by approach, scope, and level of sophistication. Most automated redesign methodologies employ expert systems and attempt to capture manufacturability problems as collections of rules or heuristics. However, even at the level of individual components, many manufacturability problems are too subtle to be hard-coded in corse rules. The fact that many problems can only be detected at the manufacturing planning level makes it difficult for existing rule-based approaches to capture design difficulties or propose reasonable alternative designs. These problems are compounded when multiple artifacts interact, not only in assemblies, but across the manufacturing enterprise. Further complicating matters is the fact that design is an interactive process and thus all of these computations must be handled in real-time.

An interactive redesign system will need to be capable of analyzing the artifact's design history, its relationship to similar parts in a company's corporate manufacturing databases or files, and the constraints imposed by the different interacting design and manufacturing teams working concurrently on the product. Some of the specific problems to be address are as follows:

- how to represent and reason about partial or incomplete designs;
- how to access and intelligently reuse legacy information (for example, in a corporate knowledge base);
- how to mediate conflicts to satisfy contradictory manufacturing constraints;
- how to provide quick responses for interactive computing environments.

These problems—and some possible approaches for addressing them—are described in the following section.

3 Challenges

3.1 Applications of Plan Retrieval and Reuse

In the area of AI planning systems, a relevant technology is that of *case-based planning*, and particularly the subarea of *plan reuse*. In general, the case based methods focus on the use of a memory of past plans for use in current situations. The analogy in manufacturing is to variant planning approaches. Two aspects of the AI technology may be particularly relevant to manufacturing design – the methods used for the retrieval of past plans and the techniques appropriate for applying the old plans to new situations. Although these are highly related, we treat them here as two separate areas.

3.1.1 Plan Retrieval

Given a set of old plans, there are several techniques that can be used in finding the one (or ones) most appropriate for solving a new problem. The simplest of these techniques is that of feature vectors, representing the plan in terms of a simple string of "keyword" like features. This technique is not dissimilar from the use of group technology codes for variant process planning [2], and thus we will not discuss it further.

More interesting, perhaps, are techniques which work by "indexing" a previous plan based on some set of relevant features arranged in an appropriate data structure for choosing features sequentially with each depending on the previous answer. As an example, a famous program called Chef [20, 18, 19] stored plans for cooking Chinese meals. A sequence of choices were made to decide which previous plan was most like a current one. The first choice might be, for example, to distinguish which type of dish (deep fry, stir fry, bake, etc.). Depending on this choice, the next might be to determine some choice of ingredients (meat or no meat, etc.) Indexed at the leaves of such a "discrimination tree" would be the particular plans for cooking those meals. The advantage of such a scheme is that a large number of plans can be accessed with time logarithmic to the total number of stored plans.

There are several problems with this indexing approach. One is that the set of relevant features must be chosen beforehand. However, if the features are to be of different importance at different times (i.e. sometimes ingredients are important, other times we might care about how long it takes to cook the meal). A second problem is that the features most useful may not be easily identifiable. This means that human intensive "knowledge engineering" work may be required to tie the cases into the indexing scheme. Where this happens, it is difficult to scale this technology to large memories, as would most likely be needed in complex manufacturing domains.

Recent work [1, 13, 25] is focusing on overcoming these problems with indexing by using more efficient, high performance, algorithms to improve memory access. This means that rather than an a priori indexing scheme, patterns of features can be dynamically checked to find relevant plans in memory. This technology allows for the automated creations of case bases and for scaling to the kinds of large memories that will be needed for storing large sets of engineering designs.

3.1.2 Plan Reuse for Manufacturing Planning

Having found a previously used plan, it is necessary to determine how to use it to solve a new problem. In variant process planning systems this is often done by simply displaying an existing process plan and allowing human editing. The techniques of *plan reuse* focus on both automatically identifying those aspects of the existing plan which need to be changed (useful in an interactive system) and in the automated planning of those changed aspects (essentially a combined generative/variant scheme).

The identification of those items needing changing requires two steps. First, a mapping must be identified between the old plan and the new problem. For example, if a previous part had only one drilled hole in it, and the new problem requires two (perhaps with different tolerances or depths), it must be determined which one is the best fit. Although a principled means for doing such mappings efficiently is still an open question, a number of heuristic approaches have been designed.

The second step in identifying (and repairing) changes requires using the mapping, determined in the first step, to direct the refitting of the existing plan for the new problem. Two techniques have shown great promise for this. The first is to develop techniques for abstracting plans into "skeletons" such that a number of specific plans would all have the same high level plan, but with different details. When a mapping is identified, the skeleton that best covers the new problem is chosen. That skeleton is then fleshed out using the details of the current problem. This generates the plan which is expected to solve the problem. One limitation with this approach is that it works best where the skeletons can be automatically identified, and it is unclear what the limitations are on domains that will allow this. [2]

A second approach that shows great promise is that of using "plan annotations" to guide the replanning effort. These annotations are information placed by the planner (human or machine) when it first solves the problem (creating the plan to be stored in memory). Similar to the "design for reuse" framework popular in programming languages, the annotation framework allows information to be stored which keeps track of which items depend on which others, and how various decisions were made. Using this information, efficient approaches have been designed to map and refit existing plans for new problems. To date, this approach has been shown to work with automated (generative) planners in AI domains, and current work is exploring the use of this technique in interactive planning and design systems [23].

3.2 Hierarchical and Partial Information Planning

Engineering design and manufacturing planning each are executed concurrently at several different levels of abstraction. For instance, design proceeds from conceptual level, through embodiment, eventually yielding a detailed design of the product. Similarly, manufacturing planning is done for individual machines, the level of the factory, and enterprise wide. Because it provides a natural way to plan at multiple levels [10, 9, 11], AI techniques for Hierarchical Task-Network (HTN) planning would seem to be ideal for this.

However, some of the barriers to developing the potential of AI planning techniques for planning in practical application domains have been the complexity of HTN planning techniques [8, 7], and the difficulty of integrating them with information about the application domain. AI planners usually represent states of the world as conjuncts of logical atoms (i.e., predicates with arguments), and represent the effects of an operator on the state by adding and deleting atoms from the state. This approach enables AI planners to reason efficiently about partially ordered plans (in which there may be several different possible acceptable orderings for the operators) [24], but it means that such planners cannot easily be used unless the operators' preconditions and effects can easily be represented within the logical formalism.

In domains such as process planning, the preconditions and effects of the planning operators are more naturally represented using solid modeling operations rather than collections of predicates. This can be handled by defining the manufacturing operators as arbitrary pieces of computer code (as in the SIPS process selection system [29] and the Tignum 2 bridge player [32]), or as geometric entities (as in the IMACS system for manufacturability analysis [30, 17, 4]). Such representations make it difficult or impossible to represent partially-instantiated operator preconditions and effects, which makes it very difficult to reason about partially ordered plans—but this difficulty can be circumvented either by generating only totally ordered plans (as in SIPS and Tignum 2), or by first generating totally ordered plans and then removing the ordering constraints after the planner has finished reasoning about the preconditions and effects of the individual operators (as in IMACS).

3.3 Incremental Design and Planning

When performing a planning or design task in many domains it is often difficult to specify in advance what the precise goals are. The process of creating a finished design can be thought of as an *incremental planning* problem, in which an existing plan is incrementally modified to satisfy new or changing goals. The designer specifies goals to the design system, and the design system constructs a design representation that satisfies those goals. To produce the next iteration of the design, the designer specifies new goals, and the design system modifies the existing design to satisfy those new goals.

However, there is one significant difference between this notion of incremental planning and incremental planning as investigated by AI researchers in the past [6, 21, 23]. Since the goals stated by the designer do not necessarily correspond to his/her ultimate intent, in order to produce the next iteration of the design it may be necessary to modify the existing design in ways that violate the goals that led to the existing design. The designer cares less about what particular goals and steps produced the current design than what the current design is, and how it differs from his intentions. It is therefore useful to have a system in which the planning process is performed interactively, with the solution approaching the users intent incrementally through iterations of the planning process. A planning system intended to function in this way must be able to take goal specifications interactively rather than all at once at the beginning of the planning process. The

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[2] To date this technique has been used when the plans are generated in a deductive logic framework, allowing logical inference mechanisms to be used.

planning process then becomes one of satisfying new goals as they are given by the user, modifying as little as possible the results of previous planning work.

The ability to interactively specify goals enables users to incrementally specify their intent in a design. A planning system that can modify solutions incrementally to match the users' changing intentions allows the system to be used in domains in which it is difficult to specify the goals of the user in advance. For example, [12] describes a system for Civil Engineering design that takes goals from a user interactively and changes the current model to satisfy these goals. The changes to the model are controlled through propagation in a constraint network, thus keeping the model consistent. The system uses a notion of minimal change to insure that the current change affects as few of the users previous intentions as possible. In this way the system allows a designer to incrementally modify a design such that it achieves their intent.

3.4 Search

In general, there may be several alternative ways to manufacture the design. How easy it is to manufacture—or whether it is even possible to manufacture it at all—may depend on which alternative is chosen. Thus, these alternatives should be generated and examined, to determine how well each one balances the need for a quality product against the need for efficient manufacturing.

One difficulty with generating and evaluating alternatives in a brute-force manner is that the number of alternatives can easily grow exponentially with the complexity of the design. One way of preventing the number of alternatives from getting out of hand is to combine branch-and-bound search technique with the use of clever heuristics for pruning unpromising alternatives. This approach has been used to good effect in the generation and evaluation of operation plans [30, 17, 4]). Furthermore, "limited-memory" search procedures such as IDA* [26, 28] and ITS [16] are being developed that can provide optimal or near-optimal solutions very quickly and with only limited memory requirements; and in at least manufacturing problem a limited-memory algorithm has been shown to provide significant improvements over branch-and-bound search [15].

3.5 Accessing and Reusing Legacy Information

As we move toward greater levels of automation in computer aided engineering environments, greater amounts of information can be captured and reused. Information about a design's history and the designers' intent can be recorded during the design process. The design's functional specifications can be modeled and stored in the corporation's databases.

During the design of a new product, tools are needed to give designers efficient and effective access to these masses of data. Further complicating matters is that the integration of this legacy information might require a corporation maintain the legacy data of its business/trading partners. Different parts of major corporations often make commitments to different data formats; likewise, different companies may use different DBMS products (or in-house software) to store their data.

To address problems such as these, it is necessary to develop a methodology for intelligent interchange of diverse, heterogeneous information. A paradigm for integrating multiple heterogeneous databases must be general purpose, i.e. it must be able to provide a "core" set of algorithms that are common across the integration task and are independent of the specific databases being integrated for a given application. This core set of algorithms may then be augmented by application-specific data/subroutines. Systems are being developed (for example, the HERMES system [33, 34, 27]) that run on distribute platforms across the Internet and integrate a wide variety of database and analysis packages. Such systems may also be used for constructing "information-gathering" agents that search the Internet for information that may be of interest in a given application.

4 Discussion

As we move toward greater levels of automation in computer-aided engineering environments, greater amounts of information can be captured and reused. One of the areas with great potential is automated redesign. In this paper we have outlined a number of problem areas to be addressed in the development of automated redesign systems, and have examined the potential use of AI techniques to address these problems.

Although the potential is great, to date this potential is remains largely undeveloped. One reason appears to be the different goals and world views of AI researchers and design researchers, and the mutual lack of familiarity between these two communities. To address this problem, we are beginning the development of a test bed in which to compare AI and manufacturing techniques.[3] We intend to develop a collection of manufacturing design and planning problems and solutions (e.g., designs, plans, and planning systems), presented in a way that is accessible to AI researchers for use as a test set or benchmark set. We hope that this will help AI researchers discover ways to apply AI techniques to manufacturing planning in a realistic manner, and possibly to discover issues arising in manufacturing that may be useful for AI in general.

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Integrated Product and Process Design of Microwave Modules Using AI Planning and Integer Programming

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Abstract: This paper describes the process planning techniques we developed for use in an Integrated Product and Process Design (IPPD) tool for the design and manufacture of microwave transmit/receive modules. Given a collection of data about the design of a microwave module, the IPPD tool uses a combination of AI planning and optimization-based tradeoff analysis to produce a collection of alternative designs and alternative process plans that have Pareto optimal values for manufacturing and purchasing lead time, process yield, cost, and number of suppliers. The IPPD tool provides a GUI for generating and examining these alternatives in real time, to help users modify the design to improve its cost and productivity.

Key words: Integrated Product and Process Design (IPPD), Design for Manufacturability (DFM), Artificial Intelligence (AI), Integer Programming (IP), Microwave Modules (MWMs)

1. INTRODUCTION

This paper describes an Integrated Product and Process Design (IPPD) tool for the design and manufacture of microwave transmit/receive modules. Microwave modules are complex electronic devices that operate in the 1--20

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GHz range. The IPPD tool was developed as part of a contract with Northrop Grumman Corporation's Electronic Sensors and Systems Division (ESSD) division in Baltimore. We designed it to combine high performance, ease of understandability by manufacturing personnel, ease of maintenance, and integration with other systems.

The IPPD tool uses a combination of Artificial Intelligence (AI) planning and integer programming (IP) optimization techniques to produce a collection of design alternatives. Each alternative is a collection of *design elements* (the electronic and mechanical parts to be used in the design) and *process-plan elements* (the manufacturing processes needed for the parts used in the design). The system considers the following design and manufacturing criteria: lead time (including manufacturing time and purchasing lead time); process yield; cost; and number of suppliers Each design alternative generated by the system is Pareto optimal in the sense that one design criterion cannot be improved without degrading the performance of another.. The system's GUI enables users to generate and examine the design alternatives in real time, in order to provide immediate feedback on how to modify the design to improve its cost and productivity.

2. MICROWAVE MODULES

Most commercial electronic products operate in the 10kHz–1GHz radio frequency spectrum. However, in the telecommunications arena, the range of operation frequency has been increasing at a tremendous pace. For scientific and commercial long-range defense applications—such as radar, satellite communications, and long-distance television and telephone signal transmissions—radio frequencies prove unsuitable, primarily due to the high noise-to-signal ratio associated with radio frequencies. Moreover, the lower-frequency bands have become overcrowded due to the overuse of these bands for commercial communications applications (Trinogga *et al.* 1991). Consequently, in contrast to other commercial electronic products, most modern telecommunications systems operate in the 1–20 GHz microwave range, and modules of such systems are called *microwave modules*.

When designing a microwave module, designers and manufacturing engineers may need to choose among a large number of parts and processes in order to meet system requirements, such as cost, lead times, quality, etc. (Boothroyd 1992, Hebbar *et al.* 1996). Parts could potentially be available in many forms (for example, a resistor could be available either with wire leads for through-hole mounting or with tabs for surface-mounting), and could be offered by a number of vendors with differing cost and quality attributes. Each of these different forms of a part could require a different set of processes in order to incorporate the part into the microwave module. The choice of these manufacturing processes depends on several factors, such as the type of dielectric material and the degree of integration of functional elements of the design.

The design task can be characterized as a problem in optimization-based tradeoff analysis. For each part that the designer specifies for use in the design, there may be several alternative parts that are suitable to be substituted for that part; and some combinations of alternatives may possibly produce better measures of overall solution "goodness." To complicate matters, some of these measures of goodness may be complimentary while others may not. For example, cost and quality are frequently directly proportional (i.e. higher quality components tend to cost more than lower quality ones), but from an optimization perspective these two attributes are at odds (generally, a designer wants to minimize cost while maximizing quality).

3. RELATED WORK

3.1 Prior Work by Others

Process planning can be defined as the act of preparing detailed operating instructions that transform an engineering design to a final part (Chang and Wysk 1985). Most work on Computer-Aided Process Planning (CAPP) has focused on the development of process plans for mechanical parts. CAPP systems have been traditionally classified as *variant* or *generative*; these are described below.

Variant process planning (which is the basis for most commercial CAPP systems) is based on the use of Group Technology (GT) coding schemes (Chang and Wysk 1985). The purpose of a GT coding scheme is to assign a fixed-lengh alphanumeric code to each design in such a way that if two designs receive the same GT code, they will require similar manufacturing processes. Given a new design, the user computes its GT code, and uses this code as a database index to retrieve a process plan for some other design having the same GT code. The user then modifies this plan by hand, to produce a process plan for the new design. In *generative* process planning, the process plan is developed automatically by the computer. The development of generative systems has been a subject of much research (for a comprehensive review, see (Shah *et al.* 1994)), but due to the difficulty of the problem, few successful commercial systems exist.

Some efforts have focused on CAPP for electronic applications (for a review, see Maria and Srihari (1992)). The PWA Planner (Chang and

Terwilliger 1987) is a rule-based system that performs planning for assembly of parts on placement machines. Sanii and Liau (1993) and others have used AI approaches to develop plans for assembling PCBs; and Liau and Young (1993) have developed a process planning and concurrent engineering system for PCBs that represents process knowledge as constraints and provides manufacturability feedback on the design.

3.2 Our Prior Work

The IPPD tool described in this paper grew out of the merger of two previous projects at the University of Maryland: the EDAPS project (Hebbar *et al.* 1996, Smith *et al.* 1997) and the EXTRA project (Karne, *et al.* 1998).

EDAPS (Electro-Mechanical Design And Planning System) was an integrated design and process-planning system for microwave modules, which incorporated interfaces to electronic and commercial CAD tools, generated process plans, and provided feedback about manufacturability, cost, and lead time. EDAPS's process-planning module is a predecessor of the one described in this paper.

EXTRA (EXpert T/R module Analyst) was intended to provide an integration of enterprise-wide product database management with a tradeoff analysis optimization mechanism (Ball *et al.* 1995). EXTRA's tradeoff-analysis mechanism is a predecessor of the one described in this paper.

4. THE IPPD TOOL

Our objective was to help users perform these tasks (see Figure 1):

- For each part specified by the designer, find alternative parts that might be suitable for substitution into the design in place of the original part (Nau *et al.*, 2000).
- For each alternative part, generate alternative "plan fragments", i.e., alternative collections of manufacturing processes to use on that part (Meyer *et al.*, 1998; Nau *et al*, 2000).
- Find Pareto optimal designs, i.e., combinations of parts and plan fragments that produce Pareto optimal values for the following criteria: cost, lead time, yield, and number of suppliers (Trichur and Ball, 1998).
- Select a design and a process plan from among the Pareto optimal alternatives (Splain, 1998).

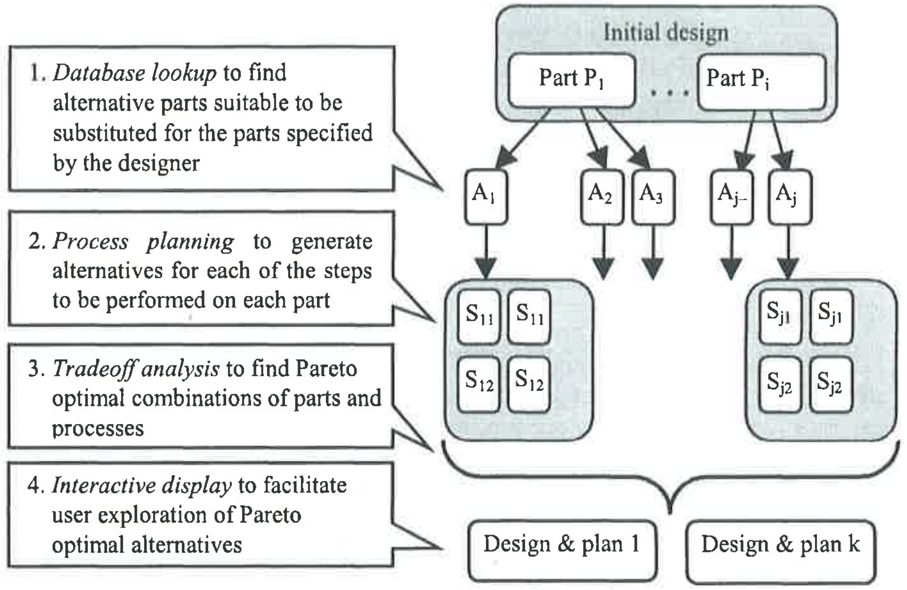


Figure 1. Generation and evaluation of alternative designs and plans.

To accomplish these tasks, our IPPD system includes:

- A *process planning module* that uses AI planning techniques to generate "plan fragments" for each part in a design. This module's knowledge base is a *process template* (see next item). For each part, the module determines (1) alternative processes for each of the processing steps that need to be performed on this part (2) the yields, setup times, and run times of each of those processes, and (3) what processes might damage this part (and are thus precluded from being used on other parts in the design).
- A *process template editor* for creating and storing process template mentioned above. The process template (see Figure 2) contains information about all of the possible processes that might be used on the part. For each process, the process template contains formulas for computing the process's setup time, run time, and yield, applicability conditions (i.e., whether or not the process is applicable to this part), and preclusion conditions (i.e., whether or not this part will preclude the process from being used on other parts in the design).
- A *tradeoff analysis module* that uses Integer Programming to generate alternate realizations of the circuit schematic; all these realizations are Pareto optimal with respect to the four criteria

mentioned above. Each realization is obtained by making specific choices among the available alternatives for parts and processes. This module includes a GUI (shown in Figure 3) whereby the user can interactively explore Pareto optimal alternatives, and an optimization 'engine' written in C++, which makes calls to the Cplex integer programming solver library. In order to obtain the process requirements and cost estimates associated with the individual parts, the tradeoff optimizer directly interfaces with the process planning module.

- *A supervisory program*, written in Visual Basic, that permits the designer to smoothly interact with the heterogeneous collection of modules described above. It also provides an interface between those modules and tools external to the system, such as the *data management* software written by Northrop Grumman personnel using Microsoft Access, and an electronic CAD package such as Hewlett Packard's Advanced Design System (formerly known as EEsof Series IV).
- *Data exchange files* used by the above modules. The data exchange is done in a manner that is transparent to the user.

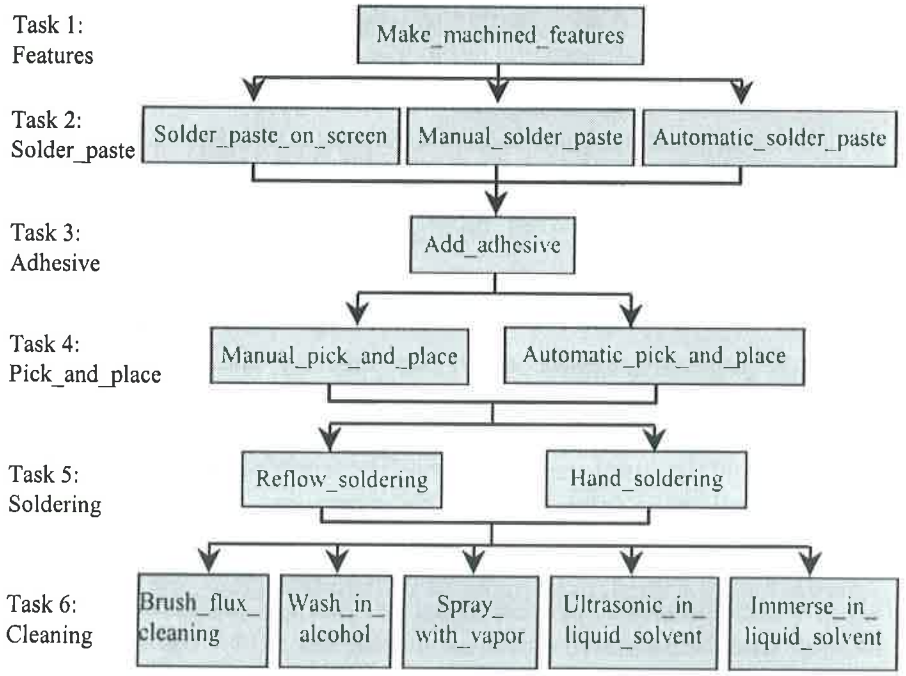
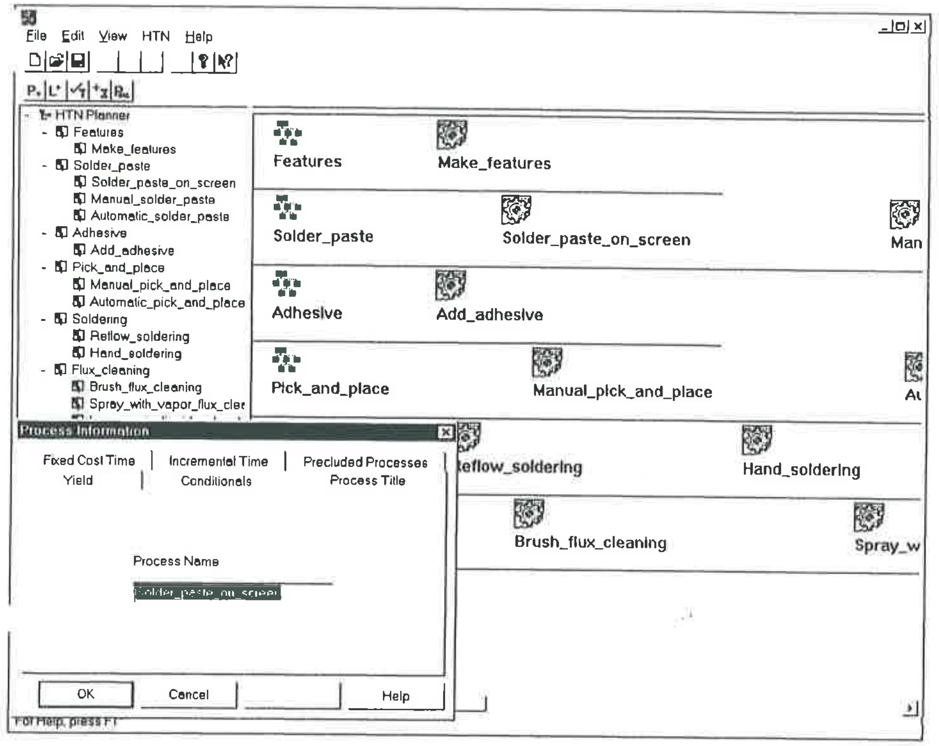


Figure 2. An example of a process template. Each node in the template represents one of the processes that might be used for some task. Within each node are formulas for the process's applicability conditions, setup time, run time, yield, and preclusion conditions.



Process Name

Solder_paste_on_screen

Figure 3. The GUI for Process template creation.

5. IMPLEMENTATION AND USAGE

5.1 Creating a Knowledge Base

To provide an easy way for design and manufacturing engineers to create and maintain process templates, we used Microsoft Foundation Class (MFC) to develop a user-friendly GUI running under Windows NT. This GUI allows the user to update the planner's knowledge base without having to modify any source code (something that was necessary in EDAPS's process-planning module). Using the GUI, the user can create the "levels" of the template (corresponding to tasks to be performed), the alternative processes at each level, and the formulas for computing the process parameters (applicability conditions, setup time, run time, yield, preclusion conditions). After creating the process template, the user can tell the system that this template should be used as the process-planning module's knowledge base .

As an example, Figure 3 shows the GUI for editing the process templates. In this example, the user is editing a process called "solder paste on screen," which is one of the alternative ways to apply solder paste step at level 2 of the process template in Figure 2. By selecting the appropriate tab of the dialog box, the user can enter formulas for setup time, run time, yield time, applicability conditions, and preclusion conditions.

5.2 Running the IPPD System

Most of the modules run on a PC under Windows NT. However, the process planning module runs as a server on a Sun workstation, and the rest of the system communicates with this module by exchanging files and commands over an ethernet connection.

As input, the IPPD system needs a list of the parts that the designer has chosen to use in a proposed design, as well as miscellaneous information such as the batch size associated with the design and the labor cost. It also needs information about the attributes of each part, including the following:

- the alternatives for each of these parts;
- the cost (in dollars) for each part;
- the defect rate (a number between 0 and 1) for each part;
- supplier information including who the suppliers are and the lead time associated with each one.

Normally, the parts list would come from a commercial CAD tool (such as Hewlett Packard's EEsof Advanced Design System, which we used during our project), and the information about the part attributes would come from a parts database. However, rather than tying the IPPD tool to any particular design tool or database tool, we wanted it to be compatible with a wide variety of design tools and database tools. For this reason, the IPPD tool reads its input from flat files rather than querying the CAD tool and database tool directly, and it is the user's responsibility to export the part information into the flat files from the CAD tool and the database tool. Once the user has done this, the IPPD tool sends this information to its process planning module, so that the process planning module can run the information about each part through the process template to determine which processes may be applicable and what their parameters are.

The process planning module determines which processes are applicable to each part by evaluating each process's applicability conditions against the list of part attributes and their values. For each process that is applicable to a part, the planner evaluates the formula for the process's run time, to compute how much time the process will take on that part. The planner then determines which (if any) processes are precluded by this part (based upon the process's preclusion conditions). It then places these results in a file that is eventually passed to the tradeoff analysis module. The process planning module also creates a file that contains the entire list of possible processes, together with their respective setup times and yields.

The input to the tradeoff optimizer is the output of the process planning module, plus the other information mentioned at the beginning of this section. Using this information, the tradeoff optimizer selects combinations of parts and processes in order to generate alternative designs and process plans. Each design and plan generated by the tradeoff optimizer is *Pareto optimal* with respect to the total cost of the parts, the total delivery lead time, the total manufacturing yield, and the total number of suppliers used.

For a complex design problem with many alternative parts and process options, there may potentially be hundreds of Pareto optimal solutions, and the problem is to find one that is satisfactory to the designer. Obviously, it would not be feasible to compute all such solutions and display them—this would overload the designer with too much information. Thus, the IPPD tool provides a GUI to help designers "zero in" on the particular Pareto optimal solutions that are of interest, by enabling them to control the "search direction" via an interactive optimization procedure.

Given the entire universe of possible parts and processes, and their associated attributes, the problem of selecting a subset of the parts (and implicitly, processes) can be formulated as an integer program (IP). The logical structure of the design (such as inclusion and preclusion conditionals for processes, etc.) gives rise to the constraints of the IP. Since we want to optimize the values of four objectives, we must consider a multi-objective IP. While arbitrary integer programs can be difficult to solve (Integer Programming is NP-hard), the underlying structure the IP formulation of the microwave module design problem lends itself to relatively fast solution by commercial-off-the-shelf IP solvers. The tradeoff optimizer includes two alternative solution procedures; see Trichur and Ball (1998) for details.

Figure 4 gives an example of the tradeoff optimizer in action. In the left-hand pane of the figure, the optimizer is currently displaying the cost associated with six different Pareto optimal solutions; the user can click on the tabs to see the values for yield, lead time, and number of suppliers. In the right-hand panes, the system has normalized all four of the criteria to the interval [0,1], so that the user can compare them simultaneously. In the boxes near the lower right-hand corner of the figure, the user can enter lower and upper bounds on the acceptable values of the objectives, and the system will produce additional Pareto optimal solutions (if any) that lie within these bounds. This provides a way for the user to "zero in" on solutions that provide the best balance of lead time, cost, yield, and number of suppliers.

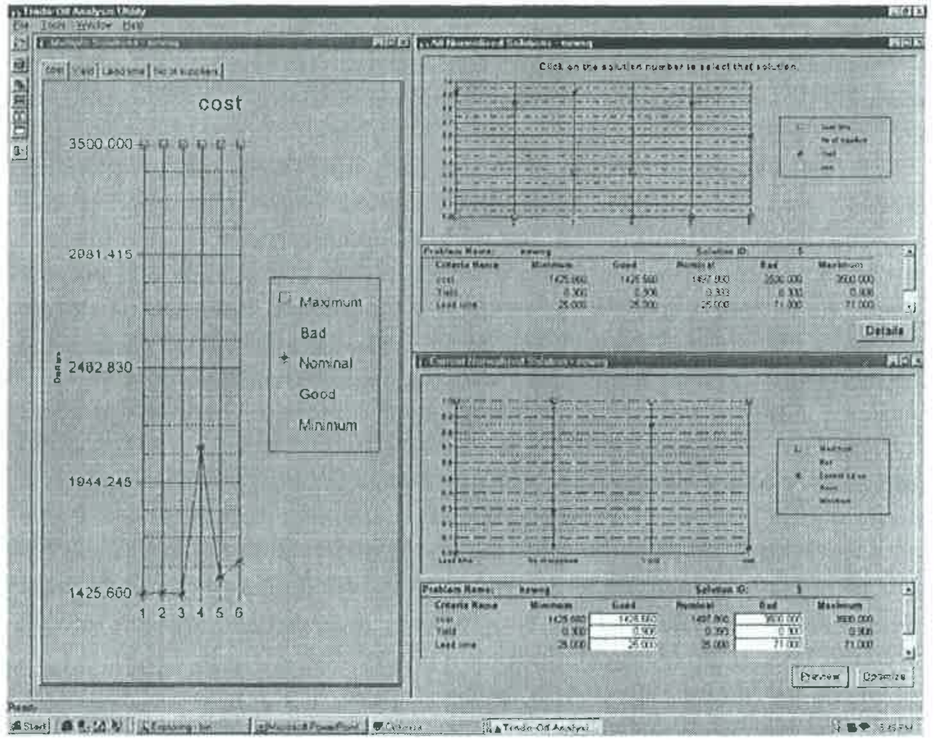


Figure 4. The IPPD tool's GUI for interactively generating and selecting Pareto optimal combinations of design elements and process-plan elements.

At each major step in the tradeoff-analysis process, a discrete optimization problem is solved. The GUI enables the user to iterate through the process, changing the relative weights that the system will give to the four optimization criteria (lead time, process yield, cost, and number of suppliers). The GUI then displays the results of the optimization process graphically so the user may determine the consequences of increasing or decreasing specific weights. This process can be repeated until the user is satisfied he/she has reached an optimal design for the problem under consideration. When the designer is satisfied with one/more solutions, the GUI recovers the relevant data (selected parts, processes, and suppliers, together with the associated values for the four objectives) corresponding to the chosen solution(s) and saves it in a file that is then passed back to the supervisory GUI of the IPPD tool.

5.3 Performance Tests

To test the tradeoff optimizer, several problem test sets were generated. The number of parts ranged between 25 and 100 with 4 to 6 alternatives per part. Using a Sun Sparc 10 workstation and Cplex 4.0 as the IP solver, the time required to find an individual efficient solution ranged from a few seconds to slightly over 2 minutes. Since, for our application, these problems are of realistic size, we feel this indicates that our IP approach provides a practical problem solving tool.

6. CONCLUSIONS

This project illustrates the benefits of a strongly interdisciplinary approach to knowledge-intensive CAD. Our research team included researchers from computer science, business, electrical engineering, systems engineering, and mechanical engineering; and in addition, we interacted extensively with our industrial partner Northrop Grumman. Our technical approach combined AI planning techniques for generating process-plan elements, IP tradeoff-analysis techniques for selecting Pareto optimal combinations of design elements and plan elements, and a GUI for user control of the system's operation.

As a follow-up to the work described in this paper, we currently are developing IPPD techniques for earlier stages of design (i.e., conceptual design), where the decisions made during the design process can have an even bigger impact (Ball and Fleisher 2000). That work is the subject of an ongoing contract with Northrop Grumman corporation.

This project also shows how research on topics motivated by complex real-world problems can produce benefits to the underlying theory. Our idea of combining AI planning and integer programming was initially motivated by the requirements of the practical problem at hand, but our subsequent exploration of this idea has led to significant theoretical advances. In particular, we have subsequently developed integer programming techniques to solve domain-independent AI planning problems (Vossen *et al.* 1999, Vossen *et al.* 2000), thereby answering one of the challenges proposed in a prominent IJCAI-97 "challenge paper" (Selman *et al.* 1997).

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How to Represent "Intelligent" Components in a Product Model

A Practical Example

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Abstract: This paper presents a multi-level approach to define a product model. It is based on the concept of what we call "Intelligent" Component. In order to be able to manage contextually the different types of knowledge involved during the design process, the multi-level model reflects the different steps of the process itself. To describe the approach an applicative example related to shaft design has been implemented. We first illustrate how to define an "Intelligent" Component for shaft design, and, then, how to extend a single-part approach to a library of mechanical "intelligent" components that allow developing complex models. It permits to show how a multi-level product model is able to capture and represent the design process from the preliminary to the detail stage, formalising all the information concerning the behaviour of the model within different application contexts.

Key words: Product model, intelligent component, multi-level architecture

1. INTRODUCTION

The reduction of time-to-market and the production of high quality and low cost products are the tight challenge that manufacturing industries have to face in order to cope with the ever-increasing worldwide competition. To reduce time-to-market, the right design must be identified as soon as possible; ideally, the solution can be summarised as follows: *right design the first time.*

As stated by a wide literature (see, for example, Woodson 1966, Yoshikawa 1981, Shigley 1983, Middenford 1996, Tomiyama 1987, and

Solid Modeling and Geometric Reasoning for Design and Process Planning

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Summary

This paper describes our work on the integration of techniques for solid modeling, geometric reasoning, and multi-goal planning, with application to computer-aided design and manufacturing. This work is being done with two long-term goals in mind: the development of a practical integrated system for designing metal parts and planning their manufacture, and the investigation of fundamental issues in representing and reasoning about three-dimensional objects. We believe this work will have utility not only for automated manufacturing, but also for other problems in design and multi-goal planning.

1. Introduction

One problem facing modern industry is the lack of a skilled labor force to produce machined parts as has been done in the past. In the near future, this problem may become acute for a number of manufacturing tasks. This has led to considerable interest in ways to automate various manufacturing tasks.

Our first work in this area was in the development of AI techniques for automated process selection. Since we believe that the rule-based approach used in most knowledge-based systems is not the most appropriate way to do process planning, we have developed a different approach, based on hierarchical abstraction. The implementation of this idea first resulted in SIPP, a process selection system written in Prolog, and later led to SIPS, a more sophisticated system written in Lisp. The evolution of SIPP and SIPS over the last several years have been described elsewhere [6,7,8,9,10,11,12], so SIPP and SIPS will not be described again here.

Recently we have increasingly become interested in integrating process planning with design and solid modeling, for two reasons. First, a good design system is essential to provide a decent interface to a process planning system. Second, there are process planning tasks which cannot be performed correctly without extensive interactions with a solid modeler. Our current work focuses on the following topics:

1. solid modeling techniques specifically suited for integration with automated reasoning systems such as process planning systems;
2. computer-aided design systems capable of reasoning about three-dimensional objects, both for use as a design aid and also for use in integrating design with process planning;
3. ways to reason about interacting features during design and planning.

These topics are discussed in Sections 2-4, respectively. Section 5 contains concluding remarks.

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2. Solid Modeling

Most approaches to the integration of solid modeling with automated process planning have essentially involved using a geometric modeler as a front end to a process planning system. Two examples of this involve the use of SIPS as the process planning system: the interface produced at General Motors between SIPS and the MBF/X-Solid CAD system [12], and the interface being built at the National Bureau of Standards between SIPS and Unicad/Romulus [1]. Such interfaces make the process planning system more convenient to use, but in order to generate correct process plans for complex objects this approach is not sufficient. What processes can be used for some machinable feature—or whether the feature can even be made at all—may depend on geometric information not available solely from the descriptions of the features. To get this information will require the process planning system to interact extensively with the solid modeler during process planning.

For example, consider the task of drilling a hole in a flat surface. Although this is usually easy, it will be impossible if some other part of the object interferes with the tool trajectory. This condition can be recognized through the specification of geometric constraints and verification of these constraints through queries to a solid modeler. In more complex examples, the process planning system will need to make a large number of such queries.

Examples such as the one above can be handled by interfacing the process planning system to an existing solid modeler—and in fact, we have interfaced SIPS to the PADL-2 solid modeler for this purpose [4]. However, our experience at building this interface, as well as our experience with several other solid modelers, has led us to conclude that most existing solid modelers are not adequate for this purpose. One reason for this is that the primary focus guiding the development of most solid modelers has been the fact that they will be used by humans. Thus, much work has been done on efficient algorithms for operations such as rendering, but less attention has been paid to providing easy and efficient ways to answer queries, retrieve pieces of the objects being modeled, and make incremental changes.

The thorough integration of a solid modeler with a process planning system (or with various other automated systems) will require the ability to do several different kinds of solid modeling operations very quickly. Some of these operations include rotating or translating the solid, extracting bounding surfaces from it, and performing set operations such as union and intersection of solids. We believe that no existing approach to solid modeling can perform all of these tasks quickly and accurately enough.

In our opinion, the approach to solid modeling which comes the closest to fitting the above requirements is boundary representation. Using boundary representations, it is easy to do fast translations, rotations, and boundary extraction, but set operations are more time-consuming. Our approach is to enhance the capabilities of boundary representations, by developing fast algorithms for set operations.

When set operations are done on solid objects represented using boundary representation, the usual approach is to check each edge of one object against every edge of the other object. This results in a cost worse than $O(n^2)$. We have developed a faster algorithm based on the divide-and-conquer paradigm, in the form of non-regular decomposition of space [13]. This results in an average-case performance which has empirically been found to be $O(n \log n)$, where n is the total number of edges of both the input and the output. We have implemented a modeling system using non-regular decomposition for the representation and manipulation of two-dimensional polygons [14]. We are extending our algorithm to handle three-dimensional objects containing both flat and curved surfaces, and we are currently building a three-dimensional solid modeler using this approach.

3. Reasoning about Features

One of the greatest problems facing the manufacturing industry today is the differences in product description in various segments of the industry. Many tools created for aiding the design and the manufacturing processes seperately, but the problem is how to provide automatic integration of these tools.

CAD-generated objects can be defined in terms of the complete geometry of the part. The descriptions contain the faces, edges and vertices making up the part. For the purpose of manufacturing, the geometry and topology are the same, but the meaning associated with this geometric structure is different, and dictates a change in the description. An object which, to the designer, is a block minus a cylinder, is to the manufacturing engineer a block with a hole and certain tolerances.

One proposed way to handle this incompatibility is *automated feature extraction*, which consists of automating the task of determining the manufacturing features of a part from its geometry. This is an extremely difficult process, and the reader is referred to [3,5] for a discussion of the complexities involved. Some of the tougher problems include (1) inferring faces needed to describe the machining operations that do not appear in the CAD description, and (2) extracting a feature which intersects or otherwise interacts with other features, without disturbing those other features.

Another approach is *design by features*, in which the user builds a solid model of an object by specifying directly its "manufacturing features." For example, one might start with a model of a piece of metal stock, and modify it by adding holes, slots, pockets, and other machinable features. One problem with design by features is that it requires a significant change in the way a feature is designed. Traditionally, a designer designs a part for functionality, and a process engineer determines which are the manufacturable features are. However, design by features places the designer under the constraints of not merely having to design for functionality, but at the same time specify all of the manufacturable features as part of the geometry—a task which the designer is not normally qualified to do.

To overcome this problem, it would be desirable to allow the designer to use not manufacturing features, but instead "design features," which may not correspond directly to manufacturing operations, but which make sense to the designer. This would require the system to translate the design features into manufacturing features after the design of the part was completed. With an intelligently chosen set of available features and ways for combining them, this should be less complicated than extracting manufacturing features from an ordinary solid model.

Given a definition of a part as a combination of design features, there may be several possible ways to translate the part into a collection of machinable features. Different translations of the same object could result in very different process plans for that object, with different costs. For example, if a wide slot bisects a pocket, it may lead to a cheaper plan if the bisected pocket is considered to be two separate machinable features rather than just one. However, if the slot is narrow, it may be better to consider the pocket to be a single feature.

We intend to develop a system for feature-based design and analysis, with the ability to reason about interactions among the features in order to make good decisions about how to translate design features into machinable features. This system will make extensive use of the solid modeler described in Section 2, and will provide information about feature interactions for use by the process planning system (see Section 4).

4. Reasoning about Interacting Features

The SIPS process selection system works well when the plans for the various features are independent. However, the problem becomes much more complicated when one tries to handle interactions among features (for example, see [2,15]).

For example, consider an object containing two holes `h1` and `h2`, both having the same diameter and the same machining tolerances. Suppose `h1` can be created by either twist drilling or spade drilling. Then the least costly way to make `h1` is twist drilling. If the depth of `h2` is sufficiently large, `h2` may require spade drilling rather than twist drilling. In this case, the cheapest way to make the entire object is to use spade drilling for both `h1` and `h2` in order to avoid a tool change—even though spade drilling would not be the cheapest way to make `h1` if `h1` were the only hole being made.

The problem described above can be characterized as a problem in multiple-goal planning, with the restriction that all interactions among the actions in the plans should be expressible in terms of partial ordering constraints, identity constraints, and the possibility of "merging" various actions [15]. In the case of process planning, each feature represents a separate goal, and merging corresponds to saving set-up or tool-change costs by performing two operations at the same time (such as the two twist-drilling actions mentioned above). In such problems, finding an overall plan to achieve all of the goals consists of selecting from among alternate plans for each of the goals and then merging certain of the actions.

As one might expect, the problem of finding an optimal overall plan is NP-hard, but it is possible to develop efficient approximation algorithms for this problem (i.e., algorithms which will produce results that are close to optimal, with reasonably fast average-case performance) [15]. We are developing such algorithms, and intend to develop them further. This will provide a way to produce process plans that take feature interactions into account.

5. Summary and Conclusions

This paper describes our work on the integration of techniques for design, geometric reasoning, and multi-goal planning, with application to computer-aided design and manufacturing. Our work focuses on the following tasks:

1. Knowledge representation and reasoning techniques for process planning. We believe that the rule-based approach normally used in knowledge-based systems is not the best approach to use in process planning. Instead, we have developed an approach based hierarchical abstraction, and implemented it in the SIPS process planning system.
2. Algorithms and data structures for solid modeling. We feel that existing solid modelers are inadequate for the kinds of interactions required for thorough integration with automated process planning systems, and we are addressing this issue by developing a new approach to solid modeling which we believe will satisfy the necessary requirements.
3. Ways to extract and reason about features and feature interactions. We believe that if a design-by-features system is to be made convenient to the designer, it is unrealistic to force the designer to design using manufacturing features. Thus, it will still be necessary to extract the manufacturing features from the model produced by the designer. However, we also believe that this task can be made less complicated than the task of extracting manufacturing features from an ordinary (non-feature-based) geometric model. We are developing techniques to handle this problem.
4. Ways to reason about feature interactions and their effects on the resulting plans. We have been developing fast algorithms to handle optimization in multi-goal planning problems, and intend to use these algorithms to handle feature interactions in process planning.

This work is being done with two long-term goals in mind: the development of a practical integrated system for designing metal parts and planning their manufacture, and the investigation of fundamental issues in representing and reasoning about three-dimensional objects. We believe this work will have utility not only for automated manufacturing, but also for other problems in design and multi-goal planning.

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