9. Van Den Hamer, P., and M. A. Treffers, 1990, A Data Flow Based Architecture for CAD Frameworks. *Proceedings of the International Conference on Computer-Aided Design,* IEEE, New York, pp. 482–485.
10. Kleinfeldt, S., M. Guiney, J. K. Miller, and M. Barnes, 1994, Design Methodology Management, *Proceedings of the IEEE,* Vol. 82, No. 2, pp. 231–250.
11. Ousterhout, J. K., 1994, *Tcl and the Tk Toolkit,* Addison-Wesley, Reading, MA.
12. Pan, J., and A. R. Diaz, 1989, Some Results in Optimization of Non-Hierarchic Systems, *Advances in Design Automation,* B. Ravani (ed.), ASME, New York, pp. 15–20.
13. Renaud, J. E., and G. A. Gabriele, 1991, Sequential Global Approximation in Non-Hierarchic System Decomposition and Optimization, *Advances in Design Automation, Design Automation and Design Optimization,* G. Gabriele (ed.), ASME, New York, pp. 191–200.
14. Renaud, J. E., and G. A. Gabriele, 1993, Improved Coordination in Non-Hierarchic System Optimization, *AIAA J.,* Vol. 31, No. 12, pp. 2367–2373.
15. Renaud, J. E., and G. A. Gabriele, 1994, Approximation in Nonhierarchic System Optimization, *AIAA J.,* Vol. 32, No. 1, pp. 198–205.
16. Sellar, R. S., S. M. Batill, and J. E. Renaud, 1996, A Neural Network-Based, Concurrent Subspace Optimization Approach to Multidisciplinary Design Optimization, Conference Paper AIAA 96-0714, Presented at the 34th AIAA Aerospace Sciences Meeting, Reno.
17. Shankar, J., C. J. Ribbens, R. T. Haftka, and L. T. Watson, 1993, Computational Study of a Nonhierarchical Decomposition Algorithm, *Comput. Optim. Appl.,* Vol. 2, pp. 273–293.
18. Sobieszczanski-Sobieski, J., 1988, Optimization by Decomposition: A Step from Hierarchic to Non-Hierarchic Systems, in *NASA Conference Publication 3031, Part 1,* Second NASA/Air Force Symposium on Recent Advances in Multidisciplinary Analysis and Optimization.
19. Wujek, B. A., J. E. Renaud, S. M. Batill, and J. B. Brockman, 1995, Concurrent Subspace Optimization Using Design Variable Sharing in a Distributed Computing Environment, *Proceedings of the 21st ASME Design Automation Conference.*

14

INTEGRATED DESIGN AND PROCESS PLANNING FOR MICROWAVE MODULES

JEFFREY W. HERRMANN, IOANNIS MINIS, and DANA S. NAU
University of Maryland

KIRAN HEBBAR
Bentley Systems

STEPHEN J. J. SMITH
Hood College

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.

Integrated Product and Process Development, Edited by John Usher, Utpal Roy, and Hamid Parsaei
ISBN 0-471-15597-7

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]

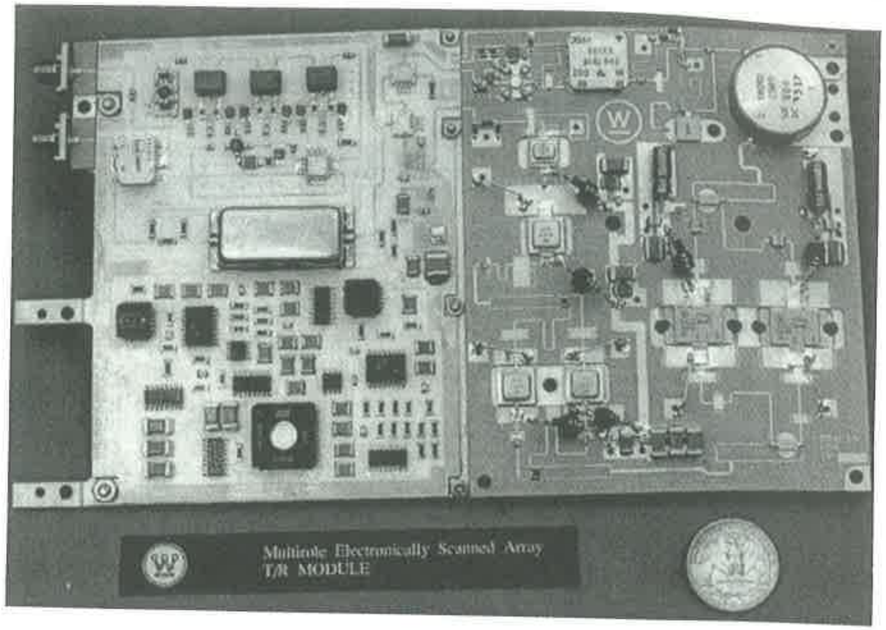

Figure 14.1 Typical microwave module.

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,

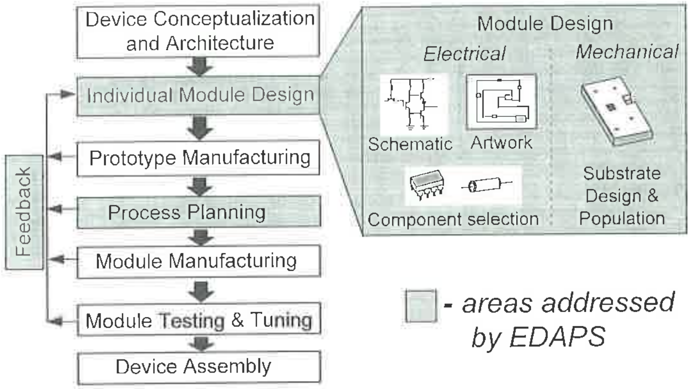

Figure 14.2 Design and manufacturing cycle for microwave modules.

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.

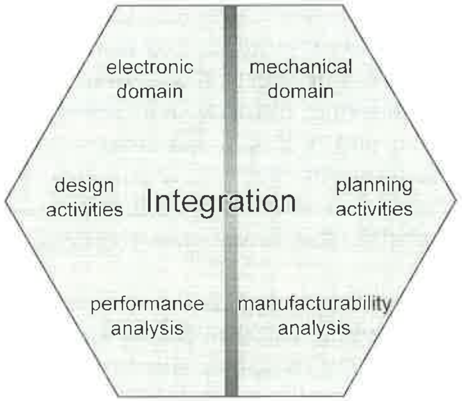

Figure 14.3 Integration of disciplines for design and manufacture of complex electromechanical devices.

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.

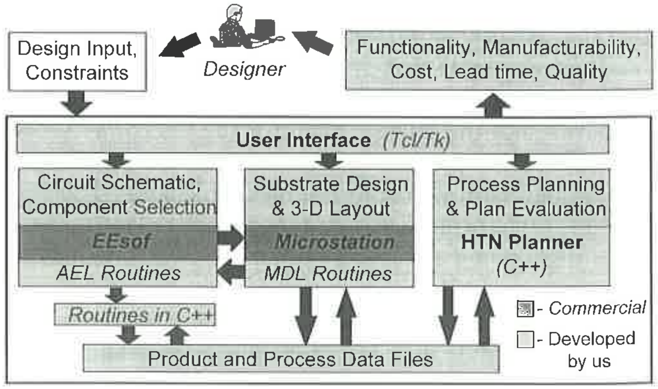

Figure 14.4 EDAPS system architecture.

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.

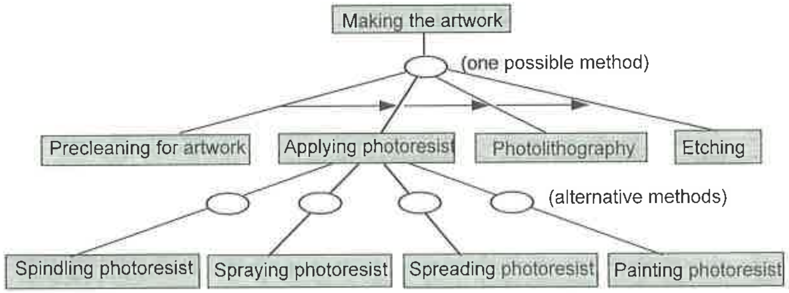

Figure 14.5 Part of the task network for microwave module manufacture.

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.

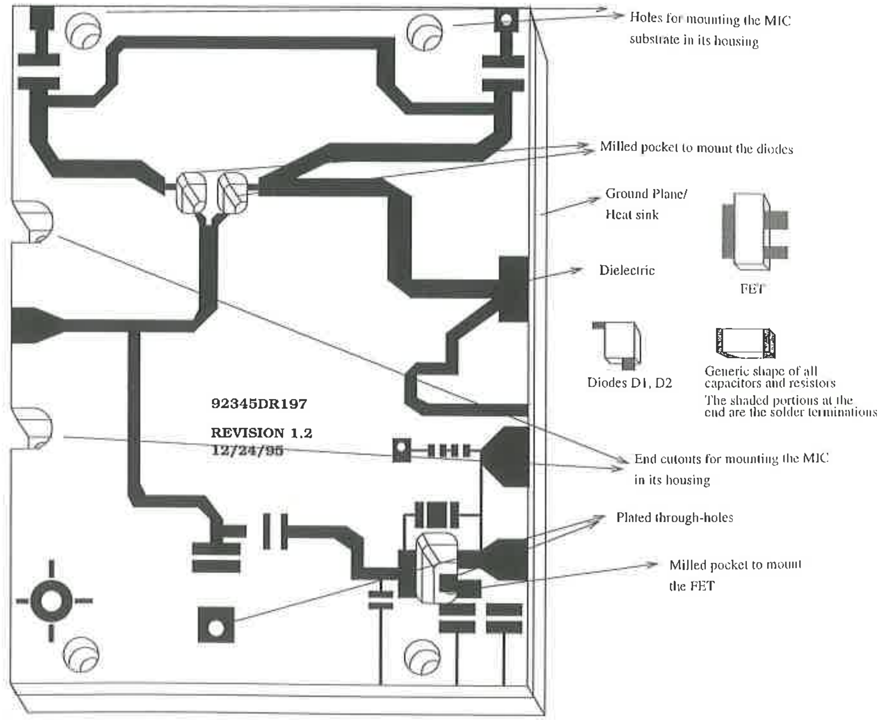

Figure 14.6 Development of mechanical features on the Mixer-IF amplifier substrate.

"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.
- 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: RNC55H237OFS
 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.

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 xj, $j = 1, \ldots, n$, 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:

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

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

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.

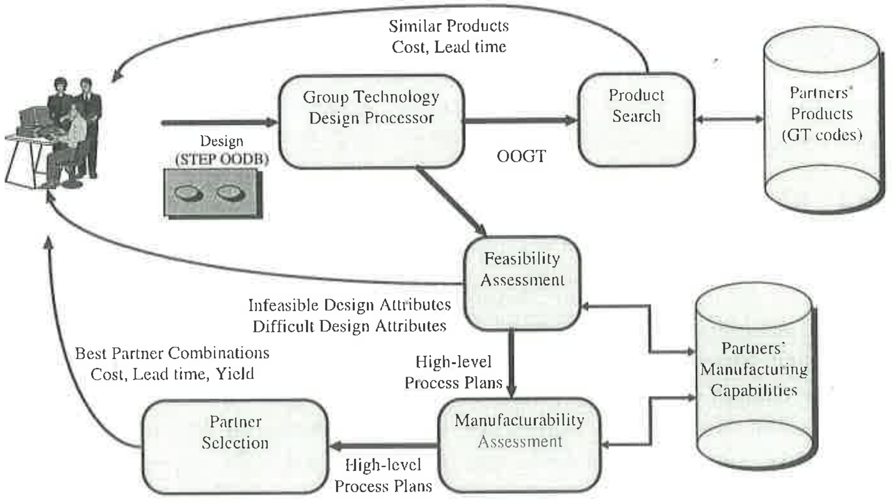

Figure 14.8 Design evaluation and partner selection approach.

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.

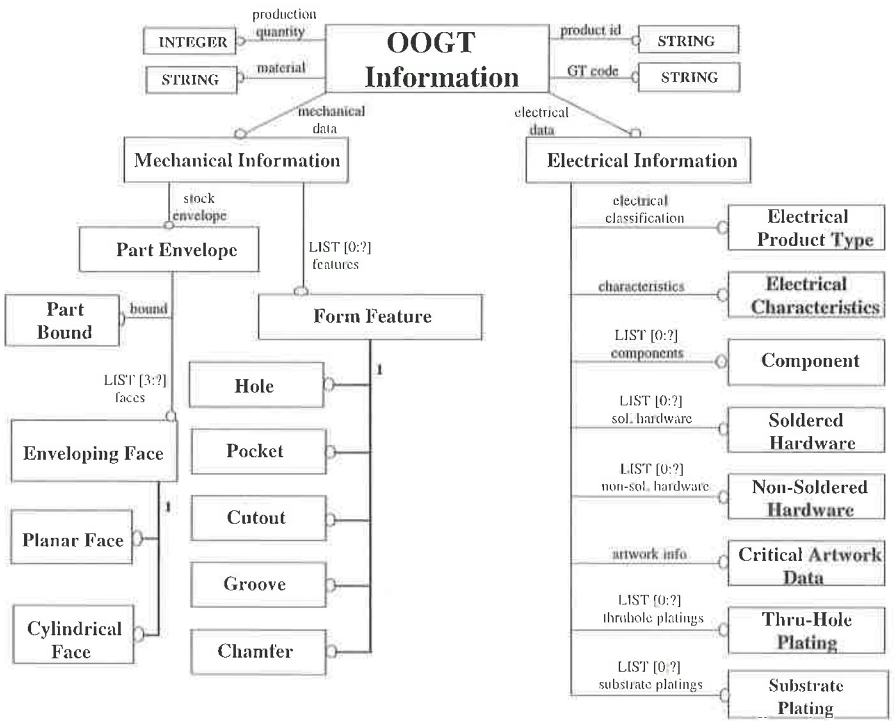

Figure 14.9 OOGT product model.

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.

ACKNOWLEDGMENTS

Portions of the work described here were sponsored by the U.S. Army Tank-Automotive Command under Grant DAAE-07-93-C-R086. The research team was led by University of Maryland researchers and included researchers from the State University of New York at Buffalo, the National Institute for Standards and Technology, Westinghouse Electric Corporation, and Martin-Marietta. The researchers at the University of Maryland were partially supported by the Institute for Systems Research under Grant NSFD CD 8803012.

Portions of the work described here were supported in part by NSF Grants NSF EEC 94-02384, IRI-9306580, and DDM-9201779, by ARPA Grant DABT63-95-C-0037, and by in-kind contributions from Spatial Technologies and Bentley Systems.

REFERENCES

1. *ACIS Geometric Modeler,* 1993, Spatial Technology, Inc., Boulder, Co.
2. Bralla, J. G., 1986, *Handbook of Product Design for Manufacturing,* McGraw-Hill, New York.
3. Brindley, K., 1990, *Newnes Electronics Assembley Handbook,* Heinemann Newnes, Oxford.
4. Candadai, A., J. W., Herrmann, I. Minnis, and V. Ramachandran, 1994, Product and Process Information Models for Microwave Modules, in *CAE/CAD Application to Electronic Packaging,* D. Agonager and R. E. Fulton (eds.), ASME, New York, pp. 33–42.
5. Candadai, A., J. W. Herrmann, and I. Minis, 1995, A Group Technology-Based Variant Approach for Agile Manufacturing, in *Concurrent Product and Process Engineering,* A. R. Thangaraj, R. Gadh, and S. Billatos (eds.), ASME, New York, pp. 289–306.
6. Candadai, A., J. W. Herrmann, and I. Minis, 1996, Applications of Group Technology in Distributed Manufacturing, *J. Intelligent Manufacturing,* Vol. 7, pp. 271–291.
7. Chenu, J. P., and H. Muller, 1989, Manufacture of Microwave Telecommunication Equipment, *Electric. Comm.* Vol. 63, pp. 159–167.
8. Clark, D. S., and W. A. Pennington, 1962, *Casting Design Handbook,* American Society for Metals, Metals Park, OH.
9. Coombs, C. F., 1979, *Printed Circuits Handbook,* 2nd ed., McGraw-Hill New York.
10. CPLEX Optimization, Inc., Incline Village, NV.
11. Currie, K., and A. Tate, 1985, O-Plan-Control in the Open Planner Architecture, BCS Expert Systems Conference, Cambridge University Press.
12. Dym, J. B., 1979, *Injection Molds and Molding—A Practical Manual,* Van Nostrand Reinhold, New York.
13. *EEsof Series IV, Version 4,* 1992, EEsof Inc., Westlake Village, CA.
14. Farag, M., 1979, *Materials and Process Selection in Engineering,* Applied Science Publishers, London.
15. Gupta, S. K., J. W. Herrmann, G. Lami, and I. Minis, 1995, Automated High Level Process Planning for Agile Manufacturing, *Proceedings of the 1995 ASME Design Engineering Technical Conferences,* O. M. Jadaan, A. C. Ward, S. Fukuda, E. C. Feldy, and R. Gadh ASME, New York, pp. 835–852.
16. Hebbar, K., S. J. J. Smith, I. Minis, and D. S. Nau, 1996, Plan-Based Evaluation of Designs for Microwave Modules, 1996 ASME Design Engineering Technical Conference and Computers in Engineering Conference.
17. Heine, R. W., C. R. Loper, and P. C. Rosenthal, 1967, *Principles of Metal Casting,* McGraw-Hill New York.
18. Harrmann, J. W., G. Lam, and I. Minis, 1996, Manufacturability Analysis using High-Level Process Planning, ASME Design for Manufacturing Conference, University of California, Irvine.
19. Hoffmann, R. K., 1987, Handbook of Microwave Integrated Circuits, Artech House, Norwood, MA.
20. *The Initial Graphics Exchange Specification Version 5.1,* 1991, IGES/PDES Organization, Gaithersburg, MD.
21. *ISO 10301-1, Product Data Representation and Exchange,* 1992, International Organization for Standardization.
22. Iyer, S., and R. Nagi, 1994, Identification of Similar Parts in Agile Manufacturing, in *Concurrent Product Design,* R. Gadh (ed.), ASME, New York, pp. 87–96.
23. Lam, G., 1995, Automated High Level Process Planning and Manufacturability Analysis for Agile Manufacturing, M.S. Thesis, University of Maryland, College Park.
24. *Microstation Version 5,* 1995, Bentley Systems, Inc., Exton, PA.
25. Ousterhout, J. K., 1994, *Tcl and the Tk Toolkit,* Addison-Wesley, Reading, MA.
26. Saaty, T. L., 1986, Axiomatic Foundation of the Analytic Hierarchy Process, *Management Sci.* Vol. 32, pp. 841–855.
27. Saaty, T. L., 1990, *Multicriteria Decision Making: The Analytic Hierarchy Process,* RSW Publications.
28. Sacerdoti, E. D., 1977, *A Structure for Plans and Behavior,* Elsevier North-Holland, New York.
29. Salomons, O. W., 1993, Review of Research in Feature-Based Design, *J. Mfg. Systems,* Vol. 12, pp. 113–132.
30. Sheridan, S. A., 1972, *Foraging Design Handbook,* American Society for Metals, Metals Park, OH.
31. Smith, S. J. J., D. S. Nau, and T. Throop, 1996, A planning approach to declarer play in contract bridge, Computer Intelligence, Vol. 12.
32. Tate, A., 1977, Generating Project Networks, *Proceedings of the Fifth International Joint Conference on Artificial Intelligence,* Morgan Kaufmann, San Mateo, CA, pp. 888–893.
33. Trinogga, L. A., G. Kaizhou, and I. C. Hunter, 1991, *Practical Microstrip Design,* Ellis Horwood, Chichester.
34. Wilkins, D. E., 1984, Domain Independent Planning: Representation and Plan Generation, *Artificial Intelligence,* Vol. 22, pp. 269–301.
35. Wilson, F. W., and P. D. Harvey, 1963, *Manufacturing Planning and Estimating Handbook,* McGraw-Hill, New York.