Integrating AI Planning and Integer Programming for Use in Integrated Product and Process Design

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Abstract

This paper describes an Integrated Product and Process Design (IPPD) tool for the design and manufacture of microwave transmit/receive modules. The tool, which was developed as part of a contract with Northrop Grumman, was designed to combine high performance, ease of understandability by manufacturing personnel, ease of maintenance, and integration with other systems. It uses AI planning to generate process-plan elements, IP tradeoff-analysis to select Pareto optimal combinations of design elements and plan elements, and a GUI for user control of the system's operation.

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 GHz range. The IPPD tool was developed as part of a contract with Northrop Grumman'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). Each design alternative generated by the system has Pareto optimal values for the following design and manufacturing criteria: lead time (including manufacturing time and purchasing lead time); process yield; cost; and number of suppliers. 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.

Microwave Modules

A typical microwave module includes a number of *parts* mounted on a *substrate*. 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. (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).

Prior Related 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 (Smith *et al.* 1997, 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). Its tradeoff-analysis mechanism is a predecessor of the one described here.

The IPPD Tool

Our objective in developing the IPPD tool described in this paper was to create a system to help the user perform the following tasks, which are illustrated in 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).

As input, the IPPD system needs a list of the parts that the designer has chosen for the design, the attributes of each part, what the possible alternative parts are, and miscellaneous information such as the batch size and the labor cost.
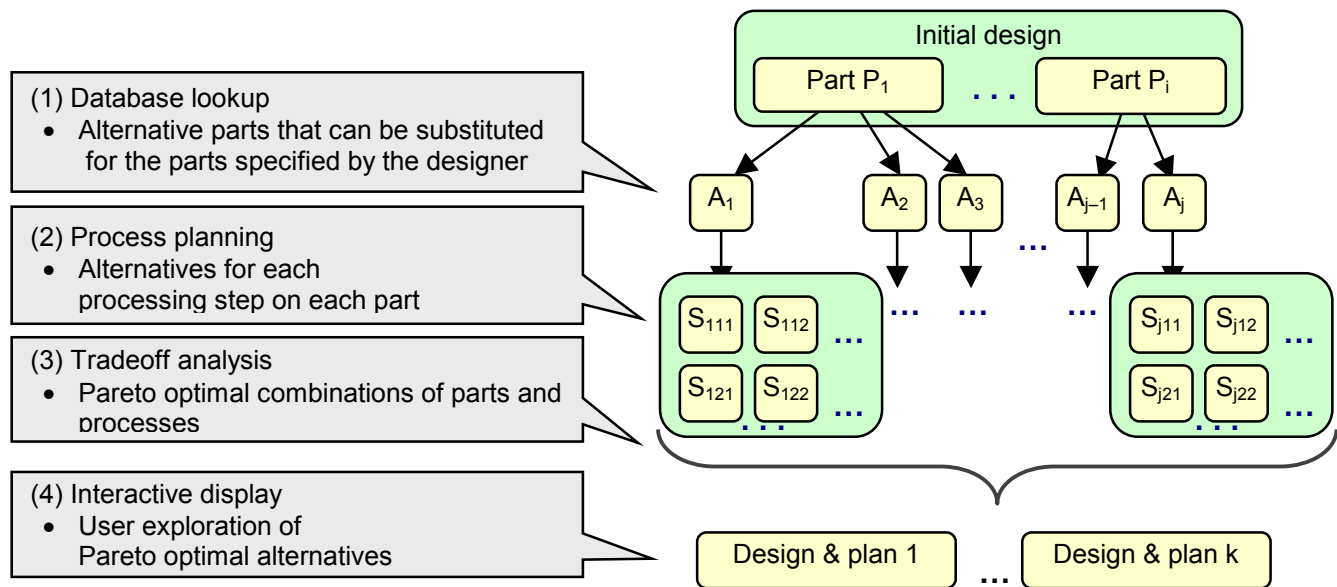

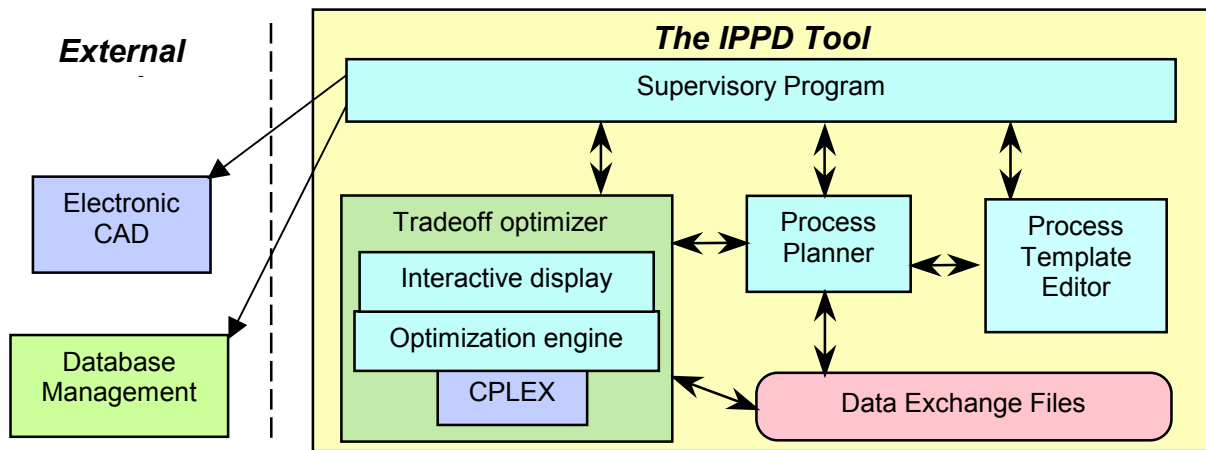Figure 1. Generation and evaluation of alternative designs and plans.

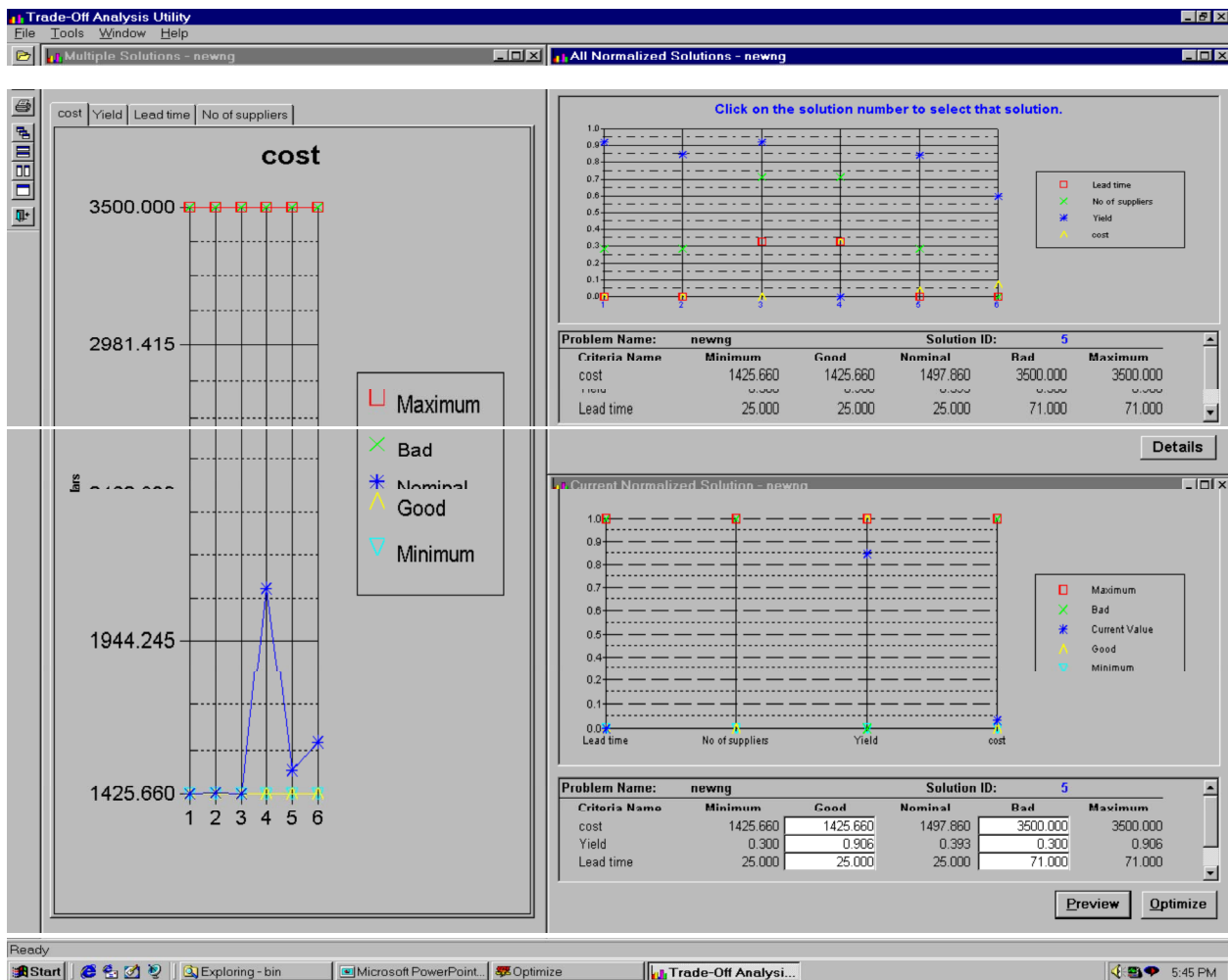Figure 2. Overall architecture of the IPPD tool.

Figure 3: The IPPD tool's GUI for interactively generating and selecting Pareto optimal combinations of design elements and process-plan elements.

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.

Figure 2 shows the system architecture of the IPPD tool. The system includes:

- A *process-planning module* (the "Process Planner" in Figure 2). This module uses AI planning techniques to generate "plan fragments" for the parts of a design. For each part in the design, the "plan fragment" generated by the process-planning module includes the following information:

  1. A list of the process steps required for this part. The list includes alternative processes for each of the process steps, together with the yields, setup times, and run times of those processes.

  2. A list of all processes that might damage this part. These processes will thus be precluded from being used on any other parts in the design.

- A *process template editor.* This module is used to create and store the domain-specific knowledge base used by the process planning module.

- A *tradeoff-analysis module* (the "Tradeoff Optimizer" in Figure 2). This module uses Integer Programming techniques to generate alternate realizations of the circuit schematic; all these realizations are Pareto optimal with respect to cost, lead time, yield, and number of suppliers. Each realization is obtained by making specific choices among the available alternatives for parts and processes. The tradeoff-analysis 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 calls optimization routines supplied by CPLEX, a commercial linear and integer programming solver. 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.* This module, written in Visual Basic, 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*, for exchanging information among the above modules. The data exchange is done in a manner that is transparent to the user.

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.

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. 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 IP optimization 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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