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Environment Tool for Manufacturing
T/R Modules

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INTEGRATED PRODUCT AND PROCESS DESIGN ENVIRONMENT TOOL FOR MANUFACTURING T/R MODULES

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ABSTRACT

We present a decision making assistant tool for integrated product and process design environment for manufacturing applications. Specifically, we target microwave modules which use Electro-mechanical components and require optimal solutions to reduce cost, improve quality, and gain leverage in time to market the product. This tool will assist the product and process designer to improve their productivity and also enable to cooperate and coordinate their designs through a common design interface. We consider a multiobjective optimization model that determines components and processes for a given conceptual designs for microwave modules. This model outputs a set of solutions that are Pareto optimal with respect to cost, quality, and other metrics. In addition, we identify system integration issues for manufacturing applications, and propose an architecture which will serve as a building block to our continuing research in virtual manufacturing applications.

1.0. Background

The pipeline approach of manufacturing after design results in an unnecessary long design cycle which consequently wastes time and money, resulting in a product that is less competitive in a global market. This problem is being addressed in many research institutions, leading to a flood of publications in concurrent engineering[2,6,9], integrated product and process design methodologies[3,7,11], and computer aided simulation tools[13].

Typically, product designs are conducted in a CAD/CAM environment where the data generated is either stored as information in a CAD drawing or in a large relational database together with a variety of other company data. The process data and models often exists in the expert's mind, not captured in electronic form. Current process models use historical and measured data in the actual manufacturing line. The data measured in the manufacturing line is often prone to errors due to inaccurate measurements, operator errors, and inadequate tools. The measuring process itself slows the manufacturing process and results in an artificially longer runtime. In an IPPD system environment, the product data in legacy databases must be integrated with the more accurate process data and models which must be acquired from process design experts.

Numerous researchers have developed decision support systems for evaluating manufacturability of T/R modules[14]. Our previous research work with T/R modules[8] addressed building cost, quality, and manufacturing rating modules and further built an expert system to evaluate different design scenarios using these models. Knowledge-based systems[15] have been attempted to address assembly of printed circuit boards. While these tools provide significant support to product designer, they do not provide an integrated platform for product and process design and do not generate and evaluate the number of design options available. In markets where lot sizes may be relatively small, we need to consider both manual as well as automated options to carry out processes (in contrast with high volume commercial applications where the operations are mostly automated).

Cost and quality trade-offs are considerable between the varying choices of components and processes. Consequently 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 performance metrics.

2.0. Introduction

The design issues related to manufacturing a product span over multiple disciplines and fields of engineering and computer science. The future of manufacturing which plays a vital role in a country's economy will depend upon how well we understand manufacturing design issues and how efficiently we integrate this heterogeneous complex systems to result in a productive virtual manufacturing environment.

The Manufacturing design environment is currently treated as two isolated design environments; the product design and the process design (Figure 1). A given process may force to change the design if it is not manufacturable. We propose data models which closely integrate product and process data and help the designer to identify the design options before manufacturing. In this paper, we will focus our attention to build a T/R Module tool for integrated product and process

design (IPPD) environment, and study the design issues that are related to architecting this product. Our research efforts will be confined to Electro-mechanical components of the microwave module designs.

Dynamic programming [2] approach to optimize the assembly processes does not appear to be practical for situations having a large search space of design alternatives. The other optimization approaches[4,5], knowledgebase techniques[10] appear to be more along the lines of work being reported here.

Our optimization techniques used in the IPPD T/R Module tool have the following capabilities:

- It considers a set of alternative conceptual/detailed designs for a given application and for each design, the complete set of alternate options in terms of functions, parts, and processes.
- Explicit expressions for cost and quality are developed and form the basis for exploring the search space of design options. The analysis takes into account the various subassemblies that comprise the final product.
- The problem is formulated as a multiobjective integer program and a solution procedure is proposed to efficiently output a set of Pareto optimal solutions.

Some of the design issues and architectural problems addressed in this paper are listed as follows:

♦ Integrate product and process designs
♦ Map legacy data from relational databases to object-oriented databases
♦ Apply multiobjective optimization techniques to manufacturing domain
♦ Develop client-server software for IPPD environment
♦ Develop object-oriented modules and libraries extendible to virtual manufacturing applications
♦ Integrate different data models (object-oriented, relational, and OR models) and address system integration issues.

The rest of this paper is organized as follows: the system architecture is defined in section 3.0. The data models related to design and process environment are illustrated in section 4.0. The optimization problem definition is illustrated in section 5.0. The section 6.0 narrates our implementation details and software platform. Finally, the section 7.0 describes concluding remarks and our future research work in this area.

3.0 System Architecture

The T/R Module system architecture is shown in Figure 2. We have implemented the system based on a workstation (SUN/UNIX) server, and a PC client (IBM Compatible/Windows NT) environment. The object-oriented database (ObjectStore) is used as a central repository for design information. It provides a single C++ programming interface.

The manufacturing data is spread across many legacy databases including DB2, Tandem, and IMS. Considering the variety of data sources, including heterogeneous databases, we have architected the problem with two-tier solution. All the design data, will be entered through the Paradox Database Frontend (PDFE). Numerous other relational DBMS (**RDBMSs**) can be interfaced with the system through a bridge (BR). The ODBC application maps queries to appropriate RDBMS through an ODBC driver. The **GUI** allows the user to interact with the optimizer and perform sensitivity analysis on the design options. The **bridge**[12,16] will act as a database gateway between relational and object-oriented databases.

The tool employed for optimization is CPLEX. The optimization routine queries the design tree in ObjectStore, and constructs the associated integer program (populates the objective function and constraint coefficient matrices used by CPLEX). The CPLEX callable library routines are used to generate the Pareto optimal solutions. These solutions are stored in the OODBMS. In addition, a cost-quality tradeoff curve is generated, which displays the cost and quality values associated with each Pareto optimal solution. The user can click on any point on this curve and examine the corresponding design using the "treebrowser" GUI.

The **Object Manager** (OM) interacts with the object-oriented database. The main functions of the OM are listed as follows:

- interface with the user (GUI) to obtain control information to the optimizer, also provide query interface to the user to display information from the ObjectStore
- interface to the bridge to obtain appropriate data and store it in the ObjectStore
- interface to the optimizer to provide initial design and scenario data to the model.

4.0 Data Models

Data models capture data organization and behavior of an application. We evaluate the functional data model (FDM). A designer conceptually designs functional blocks to perform a set of functions. Each block in the FDM in Figure 3 is a unique functional block element (FBE) which realizes a particular function of a design. Each FBE is associated with a functional bill of material (FBOM) which is a list of parts and material required for implementing this function. The

designer can associate each FBE with a set of planned processes that are required for manufacturing. This set of processes are called functional list of processes (FLOP). The Figure 4 shows the FDM for the power module

5.0 Optimization: Problem Definition

The problem we consider is to determine a set of parts and processes that realizes the design in a Pareto optimal manner with respect to cost and quality. We begin by defining some notation:

$\upsilon = \{1, 2, \ldots, V\} =$ set of generic parts,

$\upsilon_j = \{1, 2, \ldots, V_j\} =$ set of alternatives for the jth generic part,

$\rho = \{1, 2, \ldots, P\} =$ set of processes,

$c_j =$ unit cost of jth part: $j \in \upsilon_k$, $k \in \upsilon$,

$s_p =$ setup time for pth process: $p \in \rho$,

$t_{pj} =$ runtime when pth process is used for jth part,

$\alpha_j =$ defect rate of jth part,

$\beta_p =$ yield rate of pth process,

$n_j =$ number of parallel components to be used for the jth part,

$l =$ labor cost per unit time,

$b =$ batch size.

Note that n_j represents a redundancy element that is usually considered while designing electronic devices, We assume that all the above quantities are provided as input data. We now define the following decision variables:

$$x_j = \begin{cases} 1 & \text{if part j is selected,} \\ 0 & \text{otherwise.} \end{cases}$$

$$y_p = \begin{cases} 1 & \text{if process p is used in the assembly,} \\ 0 & \text{otherwise.} \end{cases}$$

$$x_{pj} = \begin{cases} 1 & \text{if process p is selected for part j,} \\ 0 & \text{otherwise.} \end{cases}$$

The expressions for cost (C_0) and quality (Q_0) are given as follows:

$$C_0 = \sum_i n_i c_i x_i + l \sum_{p,j} t_{pj} x_{pj} + \frac{l}{b} \sum_p s_p y_p, \qquad (1)$$

$$Q_0 = \prod_p (\beta_p)^{y_p} \prod_j (1 - \alpha_j^{n_j})^{x_j}. \qquad (2)$$

The above equations are essentially derived on the following basis:

Cost = material cost + runtime cost + setup cost

Quality = Yield = (process yield) (material yield).

The decision variables in (1) and (2) ensure that only those elements that are selected to be in an assembly contribute to its cost and quality. We can now linearize (2) to get

$$Q_0' = \log Q_0 = \sum_p y_p \log \beta_p + \sum_j x_j \log(1 - \alpha_j^{n_j}). \qquad (3)$$

The problem we wish to solve is the following multiobjective 0-1 integer program:

$$\text{minimize} \quad \left\{ \begin{matrix} C_0 \\ -Q_0' \end{matrix} \right\} \quad \text{subject to}$$

$$\sum_{j \in \upsilon_k} x_j = 1 \quad k \in \upsilon \qquad (4)$$

$$\sum_{p \in \rho} x_{pj} = x_j \quad \forall_j \qquad (5)$$

$$y_p \geq x_{pj} \quad \forall_{p,j} \qquad (6)$$

$$x_j, y_p, x_{pj} \in \{0,1\} \quad \forall_{j,p} \qquad (7)$$

It is well-known that a set of efficient solutions to the above problem can be obtained by solving the following parametric problem (**P**):

$$\text{minimize} \quad \lambda C_0 - (1 - \lambda) Q_0', \qquad (8)$$

subject to constraints (4)-(7),

where the parameter l ranges over the interval [0,1]. It is this version of the problem that we address in our project.

For any given l, problem **P** directly corresponds to the well-known *incapacitated facility location* problem and, consequently, is NP-Hard. However, the problem has been studied and a number of solution strategies have been reported in the operations research literature. We would like to generate a set of Pareto optimal solutions parameterized with respect to l. We need to consider efficiency and accuracy with which parametric analysis could be carried out.

The solution approach that we propose at this time arises from the observation that the number of process alternatives involved in the T/R Module design is quite small with the key processes being

- manual or automated placement (assembly) for surface mount and leaded parts,
- manual or wave soldering for leaded (through-hole mounted) parts, and
- manual, wave or reflow soldering for surface mount parts.

The small number of possible processes implies that an approach which starts by enumerating all possible process combinations (y vectors) is computationally feasible. We then note that for a given set of selected processes, that is, a

set P such that

$$y_p = \{^1_0 \quad \begin{matrix} \text{if } p \in p', \\ \text{otherwise}, \end{matrix} \tag{9}$$

problem P becomes easy to solve. In fact, it is easy to show that the following greedy assignment rule produces an optimal solution.

GREEDY_SOLUTION(P')

for i:= 1 to V /* for each generic part type */

for j:= 1 to V_i /* for each alternative of the ith generic part type*/

$$p := \frac{l \in P':t_{lj} \leq t_{mj}}{} \qquad \forall m \in P' \quad /* \text{ greedy choice of process for part } j */$$

$$cost[j] := \lambda(n_j c_j + lt_{pj}) - (1-\lambda)(1-\alpha_j^{n_j}) \quad /* \text{ cost out part } j */$$

end for

$$choice[i] := l \in v_i : cost[l] \leq cost[m] \quad \forall m \in v_i$$

/* greedily select alternative for ith generic part type */

end for

For a given set P' of selected processes, the greedy algorithm stated above first assigns the cheapest process for each part alternative. It then costs out each part alternative and subsequently selects the minimum cost alternative for each generic part type. It can easily be shown that the above algorithm generates an optimal solution.

The greedy approach however does not permit a straightforward procedure for parametric analysis with respect to l. For this purpose, consider the following reduced problem **P**(P')

$$\text{minimize} \quad \lambda C_0 - (1-\lambda)Q_0'$$

subject to constraints (4)-(7) and (9). It can be shown that the associated constraint matrix is unimodular, and hence, the feasible region for this problem is an integral polyhedron. The linear programming (LP) relaxation to this problem produces an integer solution. Standard LP software such as LINDO or CPLEX may be used to resolve this.

In summary, our approach is to solve $2^{|P|}$ subproblems, one for each choice for P'. For each subproblem, the optimal objective function value is obtained as a piece-wise linear function of l. The lower envelop of the family of these functions yields the parametric solution to the original problem **P**. The situation is shown in Figure 5.

6.0 Implementation

We have implemented the proposed system architecture in the C++ programming language environment adhering to all object-oriented programming techniques. Application programs are written in Visual C++ with the help of Microsoft foundation classes (MFC) for the GUI development. The ObjectStore supports UNIX server and PC client. The CPLEX optimizer supports C function libraries. The results of the CPLEX application (optimal solutions for the designs and scenarios) are further stored back in the object-oriented database through transactions. For larger applications we anticipate performance problems as the user invokes the optimizer iteratively to obtain a "**good**" design solution. The paradox frontend GUI is in Figure 6

7.0 Conclusions & Further Research

The integrated product and process design automation tool development is crucial to the success of microwave module product or any other avionics (electronics) product manufacturing in order to achieve low cost, high quality, short lead time, and fast development cycle time.. The research issues to be resolved are integration of databases (relational and object-oriented) with real world applications, and integrating multiobjective optimization techniques in a software system. This approach will save substantial cost to the manufacturer.

We have demonstrated the T/R Module tool in our laboratory and currently working on enhancing the tool to interface with variety of legacy databases. The bridge is currently under investigation and we need further research in this area. We plan to demonstrate this prototype at our customer site where the tool will be closely integrated with the manufacturing environment.

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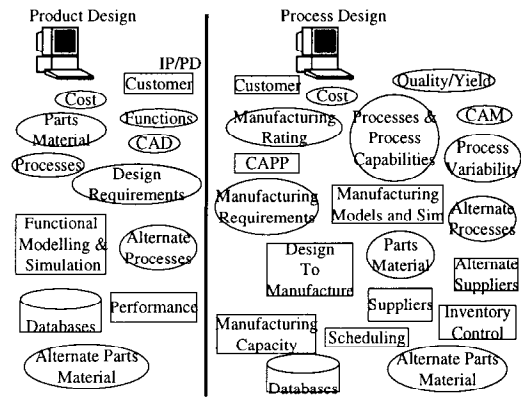
Figure 1: Integrated Product and Process Design Environment

Figure 2: System Architecture for T/R MODULE
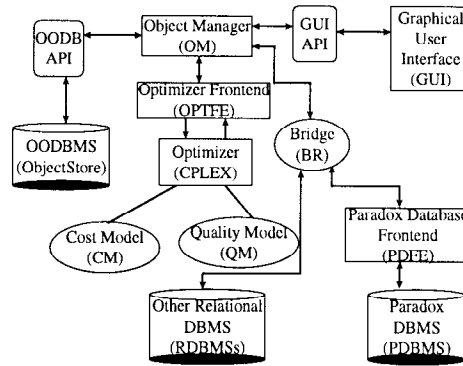
Figure 3: Functional Data Model (FDM)

Figure 4: Power Module FDM

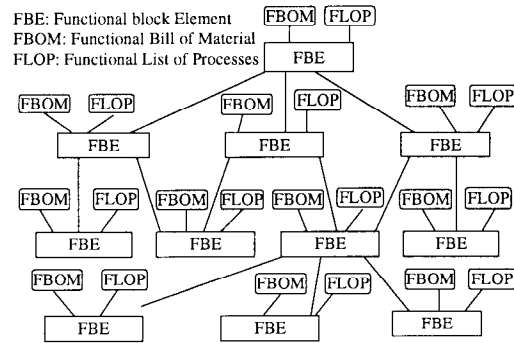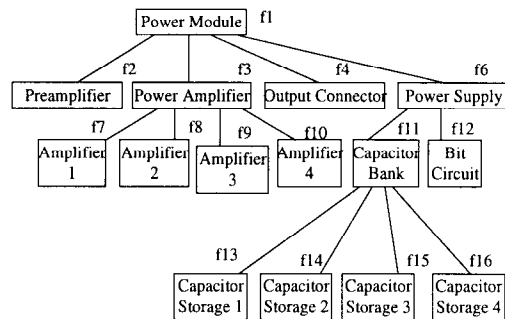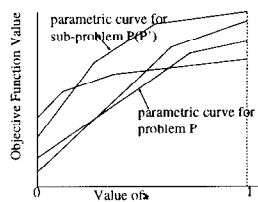**Figure 5:** Parametric Analysis with respect to λ

Figure 6: Paradox Interface T/R Module