

# TECHNICAL RESEARCH REPORT

Design for Manufacture by Multi-Enterprise  
Partnerships

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# Design for Manufacture by Multi-Enterprise Partnerships\*

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## 1 Introduction

Recent world-wide political and financial events have intensified the need to renew the competitiveness of the US manufacturing industry. The means for enabling competitiveness include fast response to the market needs for new designs and re-designs, and the ability to manufacture products at the right quality and at competitive costs. To pursue market and technology opportunities effectively, US commercial and defense industries will be relying increasingly on multi-enterprise partnerships [12]. Vertical partnering combines the strengths of multiple firms in product design, manufacture, after sales support and customer service, in order to launch superior products in the global market.

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

## 2 Computer Support for Design Automation

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

1. *Catalog-searching problems*, i.e., design problems which require selection of standard components. Considerable automation has been achieved in such problems. Currently, only a limited number of catalogs are available on-line, but we anticipate that these types of tools will gain more and more popularity.
2. *Parametric design*, in which the physical configuration of the design is known or can be easily derived from the functional requirements [10], and the designer is mainly concerned with choosing the appropriate parameters for the design. Some successes have already been reported in automating this kind of design problem, and we believe that it is a promising candidate for further automation.
3. *Creative design*, in which the designer does not know the physical configuration of the design, and must design it from scratch. Several research projects have reported interesting preliminary results (for example, see [13])—but there is a striking contrast between the relative success of automated design techniques for certain electronic problems (such as the design of integrated circuits) and the relative lack of success of automated design techniques for mechanical and electro-mechanical devices. We believe that the primary reason for this discrepancy is that for mechanical and electro-mechanical

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devices, it is much more difficult to decouple the interactions among the device requirements than it is for purely electrical devices. Thus, we believe that the best approach will be not to try to automate the design task completely, but instead to develop tools for critiquing the design as it is being developed. Analysis tools will be needed to help the designer to foresee potential problems with a variety of life-cycle considerations, such as performance, producibility, partner selection, reliability, maintainability, and so forth. Research is already underway to develop such tools [1, 8, 3, 2].

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

As designers make increasing use of multiple critiquing systems, there will be problems in coordinating these tools [9]. For example, the design that is easiest to assemble is not likely to be the design that is easiest to machine. Thus if the designer follows the advice of a design-for-machinability tool, this may cause problems with assemblability, and vice versa. It will be necessary to develop ways to reconcile such conflicting objectives, so as to avoid giving the designer confusing and contradictory advice.

### 3 Process Planning

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

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

The two primary techniques for doing process planning are the variant and generative approaches; for a survey, see [4]. Variant process planning has generally been much more successful at producing realistic process plans, but both it and generative process planning have some well known limitations. For near-term progress in process planning methodology, we envision that the most effective approach will be a hybrid approach that incorporates elements of both variant and generative process planning. More specifically, a hybrid approach to process planning would use variant techniques to retrieve process plans for existing designs that are similar to the new one, and use these plans as a starting point for synthesizing a final plan for the new design. Such a synthesis could be based on an analysis of the manufacturing processes involved—and this analysis could also be used to provide feedback about the manufacturability of the design. This hybrid approach should be able to combine the best features of variant and generative process planning, while avoiding the worst of the problems that they have individually.

### 4 Manufacturability Evaluation

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time—and thus it is important to design the product in such a way as to balance the need for efficient

manufacturing against the need for a quality product. The idea of design for manufacturability has been around since World War II [12], but progress in developing scientific methods has been slow. One of the goals of concurrent engineering is to identify design elements that pose problems for manufacturing and quality control, and provide feedback to the designer about these elements, so that manufacturability can be assured during the design stage. Most existing approaches to automated manufacturability evaluation involve rule-based systems that operate off-line; see [11] for examples.

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

- Integrating deterministic and stochastic aspects to formulate modeling strategies to predict process performance. If such an approach were used to implement tools that could be used on-line while the design process is going on, this would provide a powerful consultation tool for evaluating manufacturability. As a step in this direction, we have developed physics-based models that incorporate both deterministic and stochastic aspects of manufacturing process behavior for machining operations [14].
- Evaluating the manufacturability of a proposed design involves estimating the production cost and quality associated with manufacturing it. Since there can be several different ways to manufacture a proposed design, it is important to consider different ways to manufacture it, in order to determine which one best meets the manufacturing objectives. As a first step, we have developed a methodology for systematically generating and evaluating alternative operation plans for machined parts [3].

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

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

## 5 Multi-Enterprise Partnering

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

The manufacturability evaluation approach described in section 4 will enable a concurrent engineering team to evaluate the manufacturing complexity, approximate manufacturing cost and cycle time, and achievable quality of their design with respect to the capabilities of a multiplicity of potential manufacturing partners. This evaluation will be based on the alternative process plans developed by the methodology described in section 3, and will consider the information captured in the partner manufacturing model. Selecting an aggregate process plan should be done concurrently with partner selection since the merits of a process plan can only be evaluated relative to the manufacturer who will carry it out. Clearly, there is a need for new models to support these decision problems. Such models would select an aggregate process plan and would assign activities to either in-house plants or specific partners. In addition, the sequence of activities and flow of materials among plants and partners would have to be determined. In assigning an activity to either an in-house plant or to a partner two classes of criteria would have to be considered:

1. *The merits of assigning a particular activity to a particular plant or partner.* Some of the relevant considerations here would include cost, quality and cycle time. Any procedure used should recognize that some important criteria, for example some of the possible criteria for judging quality, might be hard to quantify.

2. *The overall merits of the activity assignments when viewed as an integrated system.* Several issues might be considered, such as the transportation and logistical requirements between partners, the capacity of individual partners relative to overall required throughput, and system reliability. For example, it may be desirable to include requirements for “partner redundancy” to avoid too great a dependency on any individual partner. To restrict overall system complexity, constraints could be imposed on the maximum number of partners or the geographic area within which the partner plants should belong.

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

An additional advantage of having established and assessed alternative production options is the capability to react, in case of cost overruns or time delays during the execution of the preferred production plan. If such deviations are excessive, then re-planning may be necessary and the remaining alternatives should be re-examined. Re-planning is more complex than the problem of selecting the optimum set of partners. The production state, as well as cost and time constraints should be considered in this case. We intend to enhance our research in production planning using Petri nets [6] to address this problem.

## 6 Database Environments for Manufacturing

One consequence of many of the issues we have discussed is the need to model and solve integrated problems that had previously been solved as independent subproblems: Such integrated models will be of little practical value without the ability to efficiently access the disparate data they require in a common format. Thus, we foresee the need for research into database technology specifically oriented toward manufacturing problems. In particular, the object-oriented (OO) data model and database environment are well-suited for manufacturing systems management. Many of the problems with the use of relational databases for manufacturing applications such as CAD motivated the development of the OO data model; hence, much work has already been carried out in the OO modeling of manufacturing data for specific design problems.

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

- Integrated models can have easy access to disparate data sources. This will reduce the overhead of constructing interfaces for a variety of data sources and sinks.
- There is rapid technology development both on group decision making tools and high speed communications systems. Appropriate data models and database systems will allow these technologies to be used by concurrent engineering teams, especially geographically dispersed groups.
- Complex interprocedure data flows and algorithmic constructs such as feedback, can be efficiently and accurately implemented. For example, versioning of intermediate solutions, which is fundamental to the design of man-machine systems, could be readily implemented using OO database constructs.
- By using constructs such as “active” database features which trigger the execution of processes in real time, OO database systems would not only improve manufacturing control and manufacturing design systems individually, but also provide an environment for a tight integration between them [7].

## 7 Conclusions

The research directions described in this paper are ambitious. In order to address them, it will be necessary to pose and solve fundamental questions in databases, planning, and optimization. In addition, to allow

for the possibility of partners carrying out details of the manufacturing task, new aggregate-level models of designs, process plans, and production plans will be needed. This research will serve as the basis for powerful concurrent engineering tools for providing feedback on design performance and manufacturability, and for evaluating production alternatives taking into account the capabilities of potential partners. Such tools are necessary to streamline the synthesis of partnerships in pursuit of technological and market opportunities. Tools of this type, together with advances in telecommunications and database systems would provide an infrastructure for fast, effective formation of multi-enterprise partnerships that could provide a significant competitive advantage for U.S. firms in the 1990's and beyond.

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