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# DESIGN FOR MANUFACTURE IN MULTI-ENTERPRISE PARTNERSHIPS: CURRENT STATUS AND FUTURE DIRECTIONS

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## ABSTRACT

To pursue market and technology opportunities effectively, US commercial and defense industries will be relying increasingly on multi-enterprise partnerships. Horizontal partnering combines the strengths of multiple firms in product design, manufacture, after sales support and customer service, in order to launch superior products in the global market. To support effective partnering, new approaches will be needed for integrating the activities of design, planning, and production. 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.

## 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 [36]. Horizontal partnering combines the strengths of multiple firms in product design, manufacture, after sales support and customer service, in order to launch superior products in the global market. To support effective partnering, new approaches will be needed for integrating the activities of design, planning, and production. As shown in Figure 1, some of the more critical issues include the following:

- design from functional specifications, taking full advantage of the capabilities of potential partners;
- predicting design performance and manufacturability (i.e., product cost, quality, and lead time) with respect to partner manufacturing facilities, and suggesting design changes to improve manufacturability;
- developing alternative manufacturing plans, and selecting optimal alternatives;
- dynamic replanning to accommodate delays in production, changes in demand, and other unpredictable events;
- integration of design, process planning, production planning, and partner selection, to enable users to determine the impact of changes to the production life cycle;
- user interfaces that enable the user to analyze, evaluate and enhance the options suggested by the system and to make intelligent decisions;
- database models and systems that facilitate integrated problem solving, most particularly, problem solving by geographically dispersed partners.

To account for the capabilities of potential manufacturing partners, new aggregate-level models of designs, process plans, and production plans must be developed. For example, whereas a "traditional" process plan defines operations to be carried out on certain machine types, a multi-enterprise, aggregate process plan would define sets of operations, or simply aggregate operations, to be carried out by manufacturing plants. This point of view is reflected in the aggregate, factory, and detailed levels shown in Figure 1. It is important to address both the fundamental modeling of

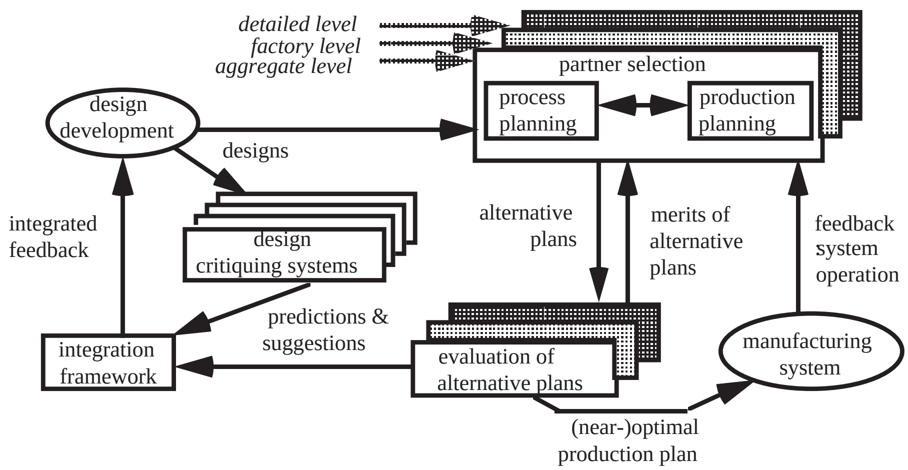


Figure 1: Design for manufacture by multi-enterprise partnerships.

design, process planning, and production planning in this context 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

### 2.1. Background

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.* Catalog-searching design problems are problems which require selection of standard components. For example, as described in [37], a catalog-searching system might search though suppliers' product catalogs to select the suitable bearing for some application, once the designer specifies the forces and dimensional constraints. Systems have been developed to do this in academic settings. Currently, only a limited number of product catalogs are available on-line, but as more of them become available, we anticipate that these types of tools will gain more and more popularity.

2. *Parametric design.* In this type of design problem, the physical configuration of the design is known or can be derived from the functional requirements [31]; one example of such a problem is the design of a transmission train for a machine tool. In such problems, 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 this case, the designer does not know the physical configuration of the design, and must design it from scratch. This is the most difficult type of design problem.

A significant fraction of engineering design problems fall in the first two categories. Even in very complex design problems, after the main configuration has been synthesized, a significant number of subcomponents can be designed using either parametric design or catalog searching. Thus, future research in these areas will help in increasing the productivity of the designer.

For the third category, creative design, the situation is more complicated. A significant level of automation has been achieved in certain problems, such as the design of integrated circuits. For the problem of how to automate more general mechanical and electro-mechanical design tasks, several research projects have reported interesting preliminary results (for example, see [42]). However, there is a striking contrast between the relative success of automated design techniques for ICs, and the relative lack of success of automated design techniques for mechanical and electro-mechanical devices.

We believe that the primary reason for this discrepancy is that for mechanical and electro-mechanical devices, it is much more difficult to decouple the interactions among the device requirements than it is for purely electrical devices. For example, changing the shape or size of a mechanical housing will change its strength and rigidity in ways that may be hard to predict without doing an extensive analysis (for example, using finite-element techniques).

Because of such interactions, automated mechanical design appears to be at least as difficult a problem as automated process planning—and automated process planning has turned out to be a much more difficult task than was anticipated when work first began on generative process planning more than ten years ago.

For the above reasons, we think it is likely that the most successful 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, to aid human designers in evaluating various design considerations such as the anticipated performance, manufacturability, and assemblability of the design. Tools for such tasks are already being developed [6, 23, 15, 12]. The next section discusses some of the research issues associated with the further development of such tools.

### 2.2. Evaluating and Critiquing Designs

Designers are being equipped with an increasingly wide variety of CAD tools for tasks such as finite element analysis, mechanism analysis, and so forth. These help to increase the designer's productivity by reducing time-consuming build-test-redesign iterations. Most of these are analysis tools which examine whether or not the design violates various constraints (such as stress, acceleration, and so forth), without offering advice about how to improve a given design. However, techniques are being developed for analyzing a design to find possible ways to improve it, and suggesting these design changes to the user [23, 14, 12, 26, 39].

As the concepts of concurrent engineering become increasingly popular, more and more downstream concerns associated with various life-cycle activities of the products are being pushed upward into the engineering design process [6, 41, 1]. This is stretching the limits of traditional design activities, making the design task more and more complex. Analysis tools will be needed to help the designer to foresee potential problems with a variety of life-cycle considerations, such as performance, producibility, reliability, maintainability, and so forth.

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. In these situations, design critiquing systems will be needed to offer advice at two different levels. Tools will be needed during the preliminary design stage, to evaluate how well the proposed design matches the manufacturing resources of different potential partners, so that the optimal combination of manufacturing partners can be selected. Once this selection has been made, additional tools will be needed to do detailed design critiquing, by utilizing critiquing systems based on the manufacturing resources of the selected partners.

Since each of these life-cycle considerations will require its own specialized analysis it is likely that designers will need to make use of a variety of critiquing systems at the same time. As designers make increasing use of multiple critiquing systems, there will be problems in coordinating these tools [28]. 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.

We use as a model for such a system the highly successful CONSOL software package [10]. The heart of the CONSOL system is a constrained non-linear optimization algorithm. The user is provided with a high degree of control over the manner in which this algorithm is applied. Specifically, the system displays the values of several objective criteria and allows the user to dynamically emphasize/weight these criteria in order to achieve an acceptable balance. While the overall structure of the system matches the requirements for an effective multiple critiquing system, the underlying optimization algorithm does not. In the manufacturing design setting, the user will typically be considering certain discrete alternatives (changes to the design). Thus, the underlying optimization problem will be a discrete optimization problem and consequently a very different algorithm and presentation of results will be required. We are optimistic that the development of such a system is within the range of current technology due to the recent advances and practical successes of discrete optimization techniques [35].

### 2.3. Support For Redesign

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

1. *Redesign for minor differences in functional requirements.* In this type of redesign problem, the functional requirements for the new design have minor differences from those of an already-solved design problem. This type of problem can be solved by retrieving the old design and making the necessary changes to adapt it for the new requirements. One example of such a problem is redesigning a gear box housing to accommodate a larger gear.

2. *Redesign for new manufacturing processes.* As new manufacturing processes are developed and become commercially viable, there is a need to redesign products to take advantage of these processes. For example, engine blocks traditionally were manufactured using casting followed by machining operations. But as die casting becomes a more economical process, the need for lighter cars is leading designers to contemplate the possibility of die-casted engine blocks. Although these engine blocks will have very similar functionality to what they had before, some redesign will be needed to adapt the old designs of engine blocks to the die casting process.

3. *Redesign for different production facilities.* The production facilities of each organization may change over time. Sometimes, new facilities or technologies are added; in other cases production facilities may become unavailable due to resource failure. Products sometimes need to be redesigned to accommodate such changes.

4. *Redesign to improve manufacturability.* In all component design procedures, the design goes through a

design cycle consisting of analysis and review of the design for cost effectiveness and quality. Ideally, the design review would take into account the capabilities and costs of the production processes to be used. However, it is not always possible to do this for all facets of the production process. After the component enters the production cycle, experienced process planners and machinists may discover that alterations in the design would be beneficial—but few companies have organizational structures that enable the design team to take advantage of this information. If tools were available at the design stage to suggest design revisions for cost containment, this would help in reducing the product realization cost. Our work toward the development of such a tool is described in [7].

Case-based approaches [3, 42] have been used to support redesign activities. In this approach, given the functional requirements for a proposed new product, a set of designs having similar functional requirements are retrieved, in a manner quite similar to what is done in variant process planning. Modifications are then made (either by a human or a computer system) to the retrieved design, to accommodate the new functional requirements. Two of the main issues in this type of approach are (1) how to develop a suitable scheme for comparing the similarity of the two designs, and (2) how to determine what modifications to make to the design. On the average, modifying an existing design should be simpler than producing the new design from scratch—but theoretical results show that in the worst case, it can sometimes be just as difficult [34]. Thus, these issues will require major effort if case-based redesign is to be successful.

## 3. PROCESS PLANNING

### 3.1. Background

The two primary techniques for automated process planning are the variant and generative approaches. In variant process planning, the process engineer uses a Group Technology (GT) coding scheme to map a proposed design $D$ into an alphanumeric code, uses this code as an index into a database to retrieve a process plan $P_0$ for a CAD design $D_0$ similar to $D$, and then modifies this process plan manually to produce a plan $P$ for the design $D$. In generative process planning, the computer system attempts to synthesize the process plan $P$ directly. For a survey of variant and generative approaches, see [17].

Although a great deal of research has been done to try to develop practical techniques for generative process planning, very few generative systems are in industrial use, because of the difficulty of devising computer systems capable of reasoning about the subtle problems that can arise in complicated process plans.

In process planning practice, variant techniques are the tools of choice: they currently support almost all practical implementations of Computer Aided process Planning (CAPP). However, variant techniques also have limitations. If the part mix varies over time, then for a new proposed design it may be difficult to find existing designs in the database that satisfy similar design specifications or require similar manufacturing processes. Furthermore, if new manufacturing processes or machines are made available in a plant and none of the process plans stored in the variant database use them, then the new processes and machines may be under-utilized unless the stored process plans are modified to use them.

### 3.2. Hybrid Planning at Multiple Levels

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. Factory-level planning is performed by a process engineer and includes a plan for a part throughout a manufacturing facility, leaving out the details of how to perform the operations in the plan. Detailed planning, for example, is performed by an n/c programmer and includes a plan for a part on a specific machine in the facility. 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. 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. The primary steps would be as follows:

**Step 1.** Given the new design $D$, retrieve (from a database) a set of plans $\mathbf{P}$ corresponding to an existing set of designs $\mathbf{D}$ having some similarity with $D$. This step would be based on an extension of variant process planning techniques; the primary extensions would be (1) replacing the usual (GT) coding schemes by a more flexible object-oriented approach for classifying and retrieving plans, and (2) extending this approach beyond the usual domain of strictly mechanical parts, to encompass a much wider variety or products. As a first step in this direction, we have extended variant techniques beyond the machining domain, to handle electro-mechanical products [19, 18].

**Step 2.** For the plans in $\mathbf{P}$, identify changes that will be needed to make them suitable for use in manufacturing the design $D$, and make changes as may be appropriate. What kinds of changes to make would depend on the level at which planning is being done. For example, if $P_0$ is a plan in $\mathbf{P}$ for some design $D_0$ in $\mathbf{D}$, then here are examples of possible changes to $P_0$ at the aggregate, factory, and detailed levels:

- *Aggregate level.* Suppose $D$ contains a component (for example, a power supply) that is to be manufactured by subcontracting. Regardless of what subcontractor was used to produce this component in manufacturing the previous design $D_0$, it may be advantageous to consult a current list of possible suppliers to decide who should supply this component for $D_0$.
- *Factory level.* If new machines or processes have been added to the factory since the time that the plan $P_0$ was written, then consider modifying $P_0$ to utilize them if this will significantly improve performance criteria for $P_0$ (such as cost, time, and product quality).
- *Detailed level.* If $D$ has tighter tolerance requirements than $D_0$, then evaluate whether the processes in $P_0$ will still be adequate, or whether different processes or process parameters will be needed to achieve the tighter tolerances. When appropriate, provide feedback information to the designer, suggesting the possibility of modifying $D$'s tolerance requirements to improve its manufacturability.

In order to perform such modifications, advances will be needed in generative process selection, process modeling, and process simulation. To date, our work in this area has focused on generating and evaluating alternative operation plans for machined parts [16, 15].

Since Step 2 involves making modifications to the plan retrieved in Step 1 (rather than constructing an entire plan from scratch), the plan-generation problem will be significantly more straightforward than full-fledged generative process planning. Several of the recent advances in feature-based process planning will be useful here [38], as well as possible adaptations [9] of AI techniques for case-based planning [3, 42] and plan modification [27].

This approach will produce one or more alternative plans for $D$. Just as in variant process planning, these plans may still need to be improved by the process engineer—but the generative plan modifications in Step 2 above will help to reduce the number of changes needed. Thus, this 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. 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. Within the emerging reality of horizontal partnering, such decisions are becoming intrinsically coupled to the design activity. Furthermore, the enhanced role of the concurrent engineering team poses unprecedented requirements to the design systems infrastructure in terms of both data modeling and data management. The inherent complexity and underlying subtleties of future partner selection call for new innovative models for supporting these decisions. These issues are discussed in the remainder of this section as well as in Section 5.

### 4.1. Product and Enterprise Data Modeling

Supporting concurrent engineering decisions within a multi-enterprise network calls for comprehensive information about product designs and manufacturing partners. For product data, it is imperative to move beyond the electronic representation of engineering drawings to the representation of life cycle product attributes. In addition, intelligent methods to access product information from the databases of multiple enterprises are required. On the other hand, critical facility data should be described by a standard information model that will capture manufacturing capabilities and performance as reflected by product cost, quality and responsiveness.

Background: product information models. Standard product representations, that can be freely shared and operated upon by different applications, are essential for product design and realization by multiple partners. The IGES product information model, which is currently the standard output of CAD systems, does not fulfill the data needs of the concurrent engineering activities described in this paper. For example, generative process planning and manufacturability evaluation cannot rely on the IGES CAD output; they require higher level product views that include, but are not limited to, material characteristics, manufacturing features and tolerance data. Such product views are currently synthesized by the various application programs and are specific to their concerns.

The STEP effort [25] appears to address these concerns adequately and shift the representation burden from the applications to the product information model. STEP comprises a number of "resources" on which a standard higher level product view, or application protocol, can be based. Such generic resources include the geometry and topology schemata as well as the form features model. On the other hand, an application protocol is specific to the product type under consideration and includes information that is pertinent to its design and manufacture. Application protocols include higher level entities, which are defined through the generic resources. For example, the application protocol for printed wiring assemblies [24] includes manufacturing features that are specific to the processes employed in their manufacture, such as plated passages. The latter are defined through generic form features, which, in turn, are defined using geometrical and topological entities. Thus, a limited set of resources can be used to build standard, high level, product information models.

We have used STEP to develop a manufacturability evaluation methodology for microwave T/R (transmit/receive) modules [19]. Our study indicated that STEP models will be able to address most of the needs outlined above. However, only a few of the generic "resources" are fully developed, and a handful of application protocols are in the development stage and have not been adequately tested. In addition, no mature tools exist to develop the necessary database schemata and populate engineering databases. Although the development of standard information models is an industry-led activity, we feel that it is necessary to incorporate and test such models in concurrent engineering research and especially in studies that focus on multi-enterprise partnering.

Manufacturing plant information model. A standard information model is also necessary to capture the production capabilities and performance attributes of a manufacturing plant. This information is essential in developing the aggregate and detailed process plans of a candidate design (see Section 3.2) and in evaluating its manufacturability with respect to the capabilities of candidate partners (see Section 2). Representing plant information in a unified way will also facilitate the objective selection of the optimum partnering option.

The description of a plant's manufacturing capabilities should consist of a comprehensive, structured representation of its manufacturing processes, the related manufacturing equipment and its key attributes, along with additional characteristics describing cost, quality and responsiveness. It is probably advantageous for the model to be hierarchical in order to provide for efficient data searches. The first decomposition of the plant model may be made on the basis of the manufacturing processes available, e.g. casting and machining (departmental level.) This level may be further decomposed into functional groups; for example, machining may include turning and milling. The functional groups may, in turn, be decomposed into the actual manufacturing equipment. Physical attributes will be employed to define each entity. For example, a lathe may be characterized by the maximum travel of its $X$ and $Z$ axes, the maximum spindle speed and the power of the spindle motor, and the accuracy and repeatability of the tool motion.

In addition to the physical descriptors of each entity, attributes that characterize manufacturing performance in terms of cost, quality and responsiveness should be defined as applicable. For example, quality information may include statistical process control limits and process capability indices at the equipment level, and yield at intermediate levels. Quality management data closely related to the information captured by the ISO 9000 standard may be included at the plant level of the model. On the other hand, responsiveness may be characterized by a distribution function. For example, the on-time delivery performance of a plant may be quantified by 80% of orders on-time, 95% of orders on time within 3 days from the due date, and 99% on-time within a week from the due date.

We have already performed work in this area that has focused on modeling the manufacturing processes employed in the production of T/R microwave modules [19]. Additional studies to develop a comprehensive manufacturing model are under way.

### 4.2. Selection of Partners

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 3.2, and will consider the information captured in the partner manufacturing model. We note that the selection of an aggregate process plan should be made 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.*
2. *the overall merits of the activity assignments when viewed as an integrated system.*

Some issues that might be considered under (1) include cost, quality and cycle time. Any procedure used should recognize that some important criteria, for example one of several criteria that might appear under quality, might be hard to quantify.

A variety of issues might be considered under (2). Overall product cost and cycle time will be greatly affected by transportation requirements between partners and the corresponding logistics. The capacity of individual partners relative to overall required throughput must be evaluated. System relaibility issues should be considered. For example, it may be desirable to include requirements for "partner redundancy" to avoid too great a dependency on any individual partner. In order to restrict overall system complexity a constraint on the maximum number of partners could be imposed or the geographic area within which the partner plants should belong could be specified.

Any solution procedure should take into account the 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. The user should be also able to examine the recommended alternatives at any desired depth. Multi-objective optimization techniques, such as those supported by the CONSOL system [10], as well as methods based on fuzzy sets may be appropriate to solve the partner selection problem. The latter is particularly attractive, since they support decisions based on qualitative criteria, such as "low cost," "superior quality," and "short cycle time."

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 [21] to address this problem.

## 5. DATABASE ENVIRONMENTS FOR MANUFACTURING

One important 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. To address this important problem, research is needed into the development of database technology specifically oriented toward manufacturing problems. In particular, it seems clear that the object oriented (OO) data model and database environment are well-suited for manufacturing systems management. Many of the problems associated with the use of relational databases to support manufacturing applications such as CAD, motivated the development of the OO data model [13]. Because of this, 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. Work addressing these issues 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. (We note that certain standards activity in the area of telecommunications systems [40] explicitly define OO model structures.) 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.

We now describe the areas in which we feel this work will have the most significant impact on manufacturing design.

- *Integrated models can have easy access to disparate data sources.* The most immediate and obvious consequence of database work will be to provide various design processes with access to disparate data sources in a common format. This will unburden the designers and implementers of design procedures from the "overhead" of constructing interfaces for a variety of data sources and sinks.

- *Group decision making tools and communications technology can be brought to bear on the work of concurrent engineering teams, most especially geographically dispersed groups.* A fundamental component of multi-enterprise partnerships and virtual factories is the solution of design problems by teams that are, in most cases, geographically dispersed. There is currently rapid technology development both in the areas of group decision making tools and high speed communications systems. These two technologies taken together allow, at least in principal, for geographically dispersed teams to work closely together on manufacturing design problems. Appropriate data models and database systems are the "glue" that will allow these technologies to be brought to bear on manufacturing problems. By developing design and planning tools simultaneously with the appropriate database environment the transition to distributed problem solving will be much easier.

- *Complex interprocedure data flows and algorithmic constructs such as feedback, can be efficiently and accurately implemented.* As was mentioned above, a very important aspect of the OO model is the fact that processes as well as data are stored in the database. This will allow for a very precise definition of all characteristics of the data flowing into, out of and between the various design and evaluation procedures discussed previously. The system structures necessary to support the algorithmic feedback loops shown in Figure 1 could be defined within such an OO model. Of particular note is the potential support of interactive man-machine decision support capabilities. For example, features such as versioning of intermediate solutions, [2] which is fundamental to the design of man-machine systems, could be readily implemented using OO database constructs.

- *Manufacturing design and control systems can be* *closely coupled.* If one considers telecommunications systems, where OO database technology is considered fundamental to future network management, it could be argued that the use of advanced database technology will have a greater impact on manufacturing control systems than on design systems [22].

Specifically, "active" database features which trigger the execution of processes in real time in response to certain conditions, are powerful constructs from a system control point of view. In this paper we do not intend to discuss in detail the area of manufacturing system control. However, it seems clear that OO database systems would not only individually improve manufacturing control and manufacturing design systems, but also provide an environment for a tight integration of the control and design sub-systems.

## 6. CONCLUSIONS

US manufacturing industries are relying increasingly on virtual manufacturing enterprises organized around multi-enterprise partnerships. To develop tools to support such activities, advances will be needed such as the following:

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

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

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