# Concurrent engineering and design: Person-centred and computer-assisted

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## Abstract

The U.S. has decreased in prominence in the global marketplace in recent years because competing countries have learned to excel in cooperation . We are investigating and developing a system that will provide:

1. computer-assisted cooperation among human designers and manufacturing engineers by promoting parallel design and manufacturing analyses and limiting the over-constraining which occurs between the two, and
2. intelligent systems support which manages the complex interactions among knowledge, data, and humans in the DFM process.

Our research efforts focus on the attainment of these two goals which are normally considered to be in conflict: concurrence in design/manufacture (which increases the number of communication channels needed) and short product development time. We believe that these goals can be simultaneously achieved by placing much of the communication burden on the computer. This essay describes the ways in which artificial intelligence research can contribute to collaboration within a design for manufacture philosophy.

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## Person-Centered Concurrent Engineering Via Computer-Assisted Cooperation and Intelligent Systems Support

## 1.0 Introduction

### 1.1 Practical Goals and Intellectual Challenges

The practical goal of Concurrent Engineering research is to enhance our world competitiveness as a nation. In order to achieve enhanced competitiveness in manufacturing, it is clear that we must move from a serial approach to a parallel approach to design and manufacturability analysis. What is not so evident are the intellectual challenges to developing an approach to achieve the practical goal. Although the terms "concurrent engineering", "simultaneous engineering", and "design for manufacture" (DFM) are mentioned quite frequently, computer-aided solutions which are robust enough to handle design and manufacturing analyses over a broad range of materials and processes are scarce.

Two primary tasks comprise the major areas of research required for the achievement of Concurrent Engineering:

1. The transfer of information and constraints among designers and manufacturing engineers must be re-modeled to reflect the parallel approach. The effect of this information transfer process on the developing part and the available options for manufacturing must be better understood. This represents a systems approach to the modeling of the parallel DFM process. Included in this analysis are representational and semantic differences in the way designers and manufacturing engineers view the part development process, and an understanding of the constraints imposed and relaxed during the design/manufacturing analysis.

2. During this information transfer process, a great deal of data (e.g. materials specifications, process information, etc.) and knowledge (e.g. process planning, cost estimation, etc.) is employed. Many systems have been developed which provide one aspect of this information (e.g. Smart CAM, Master CAM, materials databases, various expert systems, etc.). An organized method is needed which makes the right type of information available to the right person or component of a parallel DFM system at the right time. Such an information support system would greatly enhance the DFM process and render existing knowledge bases much more effective.

### 1.2 Blending AI, Design and Manufacturing Technologies

One current thrust in manufacturing research is the development and application of AI techniques to achieve Intelligent Computer-Aided Design (ICAD), Intelligent Computer-Aided Manufacturing (ICAM), and Intelligent Producibility Analysis (IPA). Components of these systems include CAD and CAPP (Computer-Aided Process Planning). Some success has been achieved in the development and commercialization of software which specializes in portions of the design-to-manufacture problem for limited domains (e.g., SmartCam). Many expert systems exist which contain useful knowledge bases pertaining to a particular process or group of related processes. However, little progress has been made in the integration of these smaller systems at a higher level: the development of practical intelligent software for attacking the more comprehensive problem of DFM. Many contend that the lack of success can be explained by the fact that research in computer-assisted concurrent engineering is in its infancy. Although this is true, we believe that the lack of progress results from the lack of emphasis on two major factors in DFM:

1. modeling of information flow and representations required for the achievement of truly parallel design and manufacturability assessment, and

2. intelligent systems which promote cooperation of (and include the participation of) human designers and manufacturing engineers in the DFM process.

A person-centered approach to parallel DFM employs the computer and associated AI technology to provide the kind of support system needed for making prior ICAD, ICAM, and IPA work useful.

## 2.0 Parallel Design and Manufacturing

### 2.1 Serial Approach

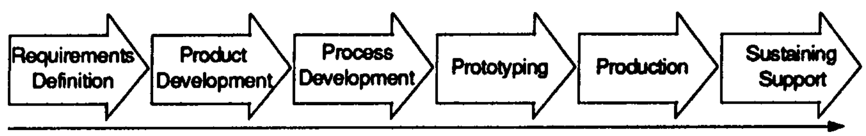


Figure 1

The serial approach to part development is well known. Figure 1 depicts this approach, in which the flow of information is dictated by the imposed structure of tasks. Each operation is completed before the succeeding task is undertaken. In a sense, the output of each prior task "dictates" the nature of the next task. Application of this model creates problems since there is a lack of communication and cooperation between design and manufacturing.

### 2.2 Current AI Work: Pseudo-Parallel Approach

Several researchers have employed AI techniques to develop intelligent design/manufacturing tools. United Technologies, Inc. developed CMPP [United Technologies, "CMPP"; Rogers and Schroer 1991; Rogers and Hubbard 1992], a computer-aided process-planning (CAPP) system. Quick Turnaround Cell (QTC) was developed by Chang [Chang 1990]. QTC employs feature-based reasoning to accomplish CAPP and the generation of NC code for prismatic parts. Diecast [Ishii 1991] is an intelligent system for making recommendations concerning diecastability of parts. Knowledge Producibility Decisionmaker, KPD, (CIM Systems, Inc.) [Piumsomboon 1991] makes recommendations concerning producibility and cost estimation for given part designs and materials. Other knowledge-based systems exist which make producibility recommendations concerning particular types of materials (e.g. metals [Brewer 1990], plastics [Ishii 1991], and composites [Messimer and Henshaw 1991]). Several commercial systems exist as well (e.g. SmartCAM, MasterCAM, etc.). Most of these systems either specialize in one block of Figure 1 (e.g., process development) or perform analyses in series, as in the serial model. For example, QTC, Diecast, and KPD each begin with a fully-specified CAD design. Manufacturing input begins after design specifications are developed. There are several reasons why the pseudo-parallel approach has been employed in these systems:

1. A good model of the dynamic interactions between design and manufacturing in a truly parallel process has not yet been developed. It is impossible to codify that which is not well understood.

2. Some tasks which are required in the concurrent engineering process cannot be adequately handled by computers.

The result is that there currently exist many "pieces" of the intelligent CE "puzzle", but there is no mechanism for "putting the pieces together." Existing systems provide the means for handling a well-defined portion of the DFM process. There is a great need for a higher-level mechanism that "understands" the process and pieces of DFM. We are investigating and developing a system in which manufacturing and design data and knowledge are exchanged between cooperating engineers. Attempting to solve the problems of Intelligent CE with the various software pieces but without a cooperation mechanism is analogous to attempting to solve optics problems with a trigonometry software package and a calculator but no theory. A higher-level model is needed to go from the problem statement to the calculations.

### 2.3 Modeling Dynamic "Interaction": A Parallel Approach

Figure 2 illustrates the parallel approach to DFM and the underlying concurrent information flow model. Each type of information (represented by squares) is needed to develop a complete product specification, but there is no serial constraint as in the previous model. The product does not have to be completely specified before process planning analysis begins. The output of a prior block no longer completely constrains the task in the following block. The complex interdependencies among blocks are used to drive the design process. As the design develops, these interdependencies create myriad constraints emerge. Design and manufacturing decisions are interleaved, with the computer aiding in the generation of choices at each step in the analysis. Choices made by either the designer or the manufacturer serve as constraints on the possible choices at the next stage in product development. These constraints are not limited to serial movement among blocks, however.

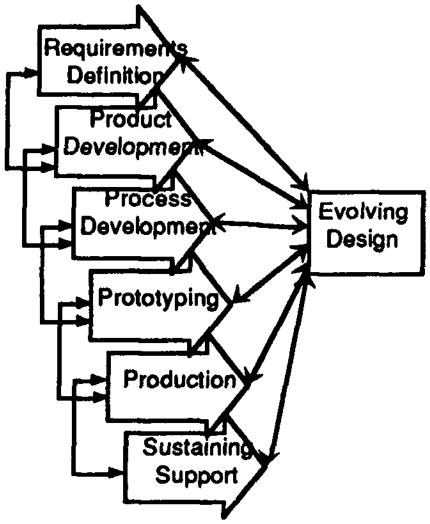


Figure 2

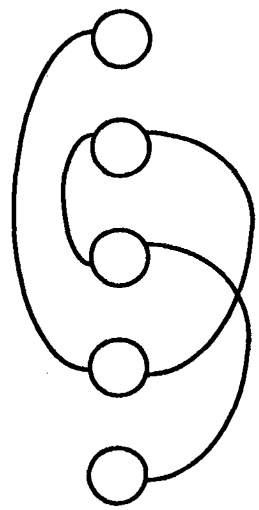

Figure 3

Figure 3 depicts social-communication model of information flow. It represents the social interactions and communication paths among human designers and manufacturing engineers during the DFM process. Once again, interaction is not limited to a serial structure. It is important to note that the pattern of interaction is highly dependent upon the individuals (represented by the circles) and on the characteristics of the particular part to be designed. This is precisely why it is so difficult to use AI techniques in DFM. The pattern of interaction is very dependent on the design context.

## 3.0 Capitalizing on Our Most Valuable Asset: Human Creativity

"Letting computers worry about details and recognize simple patterns while humans supply the imagination would lead to fruitful partnerships." (Taylor 1988)

### 3.1 Human Ability versus Machine Ability

Humans and computers, with their inherent strengths and weaknesses, can accomplish much together if they are appropriately matched. Human weaknesses tend to be the computer's strengths and vice versa. Humans are very good at working from generalizations and recognizing broad patterns. Computers are better at keeping track of details. Humans can more readily determine relevancy of an item to a particular problem, whereas computers are more capable of arithmetic operations and look-up in databases. Humans possess common sense about the physical world; computers merely do what they are instructed to do regardless of whether the actions exhibit common sense. Humans can pay attention to many things at once;

they can take in many inputs simultaneously and draw a single, relevant conclusion. Computers, on the other hand, are better at producing a lot of output based on a small amount of input.

Recent research into the practice of design [Ehn 1989; Ehn 1992; Floyd 1987; Kukla et.al.. 1992, Winograd and Flores 1986] have illustrated the way in which the interactions of various individuals with various perspectives contributes to the overall "goodness" of the product being designed. This research also makes clear the need for effective communication among human designers, and the implausibility of reducing the design process to a collection of algorithms. This strongly suggests that software systems ought to facilitate human design efforts and ought not to be built as replacement or "deskilling" devices.

These considerations make it clear that there should be both a division and coordination of labor in DFM. Computational systems are good at generating alternatives, e.g. what is possible, at a particular stage in the design, and humans are good at constraining the number of alternatives from a given set. Computational systems are good at storing vast amounts of data and knowledge (e.g. materials databases, process information, CAPP systems, etc.) and accessing them quickly, and humans are good at appraising the value and significance of information. Computational systems are good at distributing and managing communications, and humans are good at generating what needs to be communicated. Computational systems are of great value in DFM if they enhance the human creative design process, and if they make appropriate knowledge available to human designers and manufacturing engineers.

### 3.2 Promoting Cooperation and Providing Knowledge

Several "social-interaction" problems inhibit the cooperation among human designers and manufacturing engineers during DFM. These include busy schedules, attempts by factions to drive the design process, and semantic differences in each faction's view of the evolving product. The DFM process becomes inconvenient and stressful, with each faction attempting to overconstrain the work of the other faction. Options may be unnecessarily narrowed and miscommunication may occur. These human problems are intensified because the DFM process requires vast amounts of information. Both databases and knowledge bases are needed to make DFM decisions. Databases for CAD, machines, tools, materials, fixtures machinability, costs, etc. are required. Knowledge bases for material selection, process selection, machine selection, tool selection, fixture selection, process sequencing, etc. are also needed. [Chang 1990]. Human designers and manufacturing engineers can benefit greatly from a computerized intelligent support system which accesses these components at the appropriate points in the design process.

Eppinger [1992] has shown that a conflict exists between the goals of concurrent engineering and rapid product development. As more people become involved in the communication process, progress slows down. Eppinger developed a method for determining which processes should be concurrently developed in groups during the design of a product.

The groups are then treated as a serial system. The computer-assisted support we are developing allows both goals to be approached simultaneously by providing the information "connections" needed to obtain a truly concurrent design process. In contrast to the human communication problem, computers can rapidly access and make available the knowledge from a wide variety of knowledge bases and databases (e.g., object-oriented information concerning plastic materials). Product design can proceed rapidly, while at the same time, much information can be brought to bear in the choices made during design.

## 4.0 Human Creativity, Computer-Assisted Cooperation, and Intelligent Systems Support

### 4.1 Information Flow

DFM can be viewed as the development of a cost-effective part design and accompanying manufacturing specifications (e.g. materials, processes, process plan, etc.) within design and manufacturing constraints. These constraints include:

1. desired part functionality,
2. material properties and availability,
3. machine tool properties,
4. cutting tool properties,
5. setup requirements,
6. cutting parameters (speed, feed, etc.),
7. cost,
8. tolerance specifications,
9. manufacturing processes.

These constraints are complex and interdependent, and generate diverse reasoning needs.. Manufacturing processes must be properly sequenced, which requires a temporal reasoning element. Placement of features, tolerancing, and generation of NC code requires spatial reasoning capabilities. Causality (cause-and-effect reasoning) is necessary to model interdependencies among the factors listed above. Such diverse reasoning techniques are needed to answer questions such as, Does the relaxing of a tolerance constraint allow for a less expensive manufacturing process? or Does the use of a more expensive material reduce the manufacturing cost?

Other difficulties arise from the differences among various manufacturing processes. In composite manufacture, the choice of material is much more tightly bound to a particular process or set of processes than in many other types of manufacturing. Semantics can be a problem across types of manufacturing processes, as well as between manufacturing and design. For example, a milling machine operator may refer to a part as a piece of stock with a slot, whereas in diecasting terminology it would be a part with two parallel ribs. The way in which features of a part are described is often dependent on the manufacturing process chosen.

An Intelligent DFM system must be able to translate from its internal representation of a part to the appropriate semantic description for the chosen process and for the humans interfacing with the system.

Further, different players in the concurrent engineering arena view a given part in different ways. Designers initially have a relatively high-level, functional view of the part. This functional view is translated to a low-level, structural view during CAD development. Process planners view the part in several ways: a high-level, functional view is needed in planning manufacturing sequences, whereas a more low-level view is needed to incorporate tolerance constraints. A low-level view of the part is used to generate NC code.

An Intelligent DFM system must be capable of viewing the same part in a variety of ways to accomplish the necessary reasoning tasks. Moreover, the system must take into account both design and manufacturing considerations in a parallel manner. This kind of reasoning requires a control component within the intelligent system which is capable of tracking the progress of part development. The control component must be able to access pertinent information from databases and knowledge-based modules in a timely manner. Control functions are needed to provide the human designer and manufacturer with appropriate views of the part at appropriate times, and assist in eliciting important design and manufacturing attributes during part development. A true Intelligent DFM tool must have knowledge of the flow of information. It is this knowledge which allows the system to effectively utilize expertise about design and manufacturing.

To illustrate this process, an example of a bridge beam design will be given throughout the next several sections of this proposal.

The beam design begins with the following initial specifications, entered by the designer:

1. maximum load-bearing requirement: 36 kips
2. span length: 36 feet

The DFM system uses this information to constrain choices among available materials/processes for beam design. This information is also used to form test conditions that the part must pass. The initial specifications cannot be violated. The system searches a materials database to arrive at a candidate list. The candidate list is then rated according to cost factors. The costing knowledge base for construction materials specifies total cost as a function of manufacturing cost, raw material cost, cost of maintenance, and cost of construction [$C_T = f\ (C_{mf} + C_{rm} + C_{mn} + C_{cn})$]:

Candidate Materials in Order of Preference Regarding Cost:
1. prestressed concrete
2. reinforced concrete

3. steel
4. reinforced beams
5. timber
6. truss

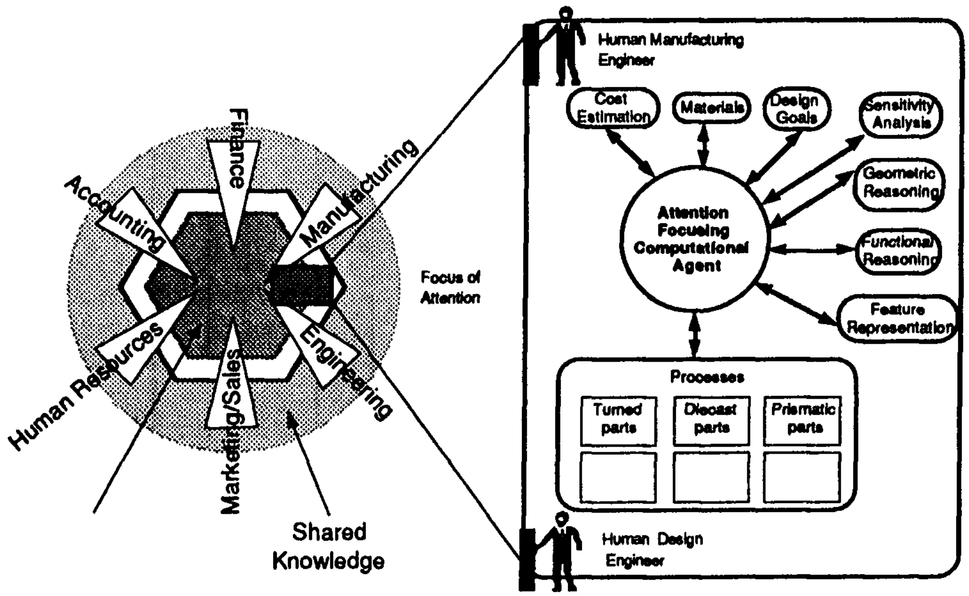


Figure 4

Figure 4 depicts the need for an integrated, intelligent CE system which incorporates the human designer and manufacturing engineer. Each component within the integrated system represents one of the "pieces" of the CE process. The system functions as a group of specialized agents which collaborate in DFM.

Each agent in the DFM system represents a specialization (in reasoning type or knowledge) which is a necessary part of the analysis. These specializations include (but are not limited to):

1. manufacturing processes,
2. materials,
3. cost estimation,
4. geometric reasoning,
5. functional reasoning,
6. feature representation,
7. design goals, and
8. sensitivity analysis.

Each agent contains a form of part representation which is best suited to its function.

The human designer and manufacturing engineer interact with the system in a mixed-initiative mode. The humans are viewed by the computation part of the DFM system as specialized agents. The attention-focusing controller presides over the agents, keeping track of the state of the evolving design, initiating appropriate agent actions, and passing pertinent information between agents. At appropriate points in the analysis, the DFM system presents knowledge and/or constraints to the human designer. The designer is allowed to make decisions (e.g., concerning which features to choose in order to achieve a certain functionality in the part) by drawing upon the knowledge presented and staying within the constraints imposed (e.g., because of producibility considerations). At other points in the analysis, the DFM system interacts with the human manufacturing engineer in a similar fashion. With this approach, the DFM system maintains a feedback loop which simultaneously incorporates the knowledge, constraints, and decisions concerning both design and manufacturing. This process facilitates the practice of concurrent engineering.

Other research work has been undertaken to structure information from a variety of sources in a constraint-based planning framework in order to achieve intelligent concurrent engineering [Lu et al. 1989; Descotte and Latombe 1985]. The proposed approach differs from previous work in that human creativity and cooperation are promoted and an explicit computational agent is included which intelligently directs the information flow during DFM analysis. Prior research [Interrante 1991] in the integration of state-of-the-art intelligent producibility analysis tools and current NSF research at Chrysler Corporation has been used as the starting point for the study of information flow in the DFM.

To continue the beam design example, the list of possible materials ordered by cost is presented to the human engineer. The human can then choose the desired alternative. Once a material is identified, the human employs the CAD agent in the system to begin a preliminary loading analysis for the bridge. The next step is for the designer to use the CAD agent to design the cross-sectional shape The proposed system provides cost information for the particular shape by searching appropriate material cost databases and informs the user of the current results. This technique provides he human designer with feedback concerning the costs of a particular design. The design can be changed to reflect the needs of the budget if required. Alternate materials can be chosen for the given CAD design, and costs will be re-calculated accordingly.

### 4.2 Computer-Assisted Cooperation

An AI approach to DFM should be employed, if it contributes to the goal of enhanced global competitiveness in manufacturing. In order to make such a contribution, the DFM system must incorporate human creativity. A distributed, networked computer system is needed to incorporate the input from human designers and manufacturing engineers as well as expert systems, databases, and object-oriented simulation systems. By working on the evolving design through the intelligent DFM system via a network, the amount of face-to-face meeting time can be reduced, and the evolving design history can be stored accurately.

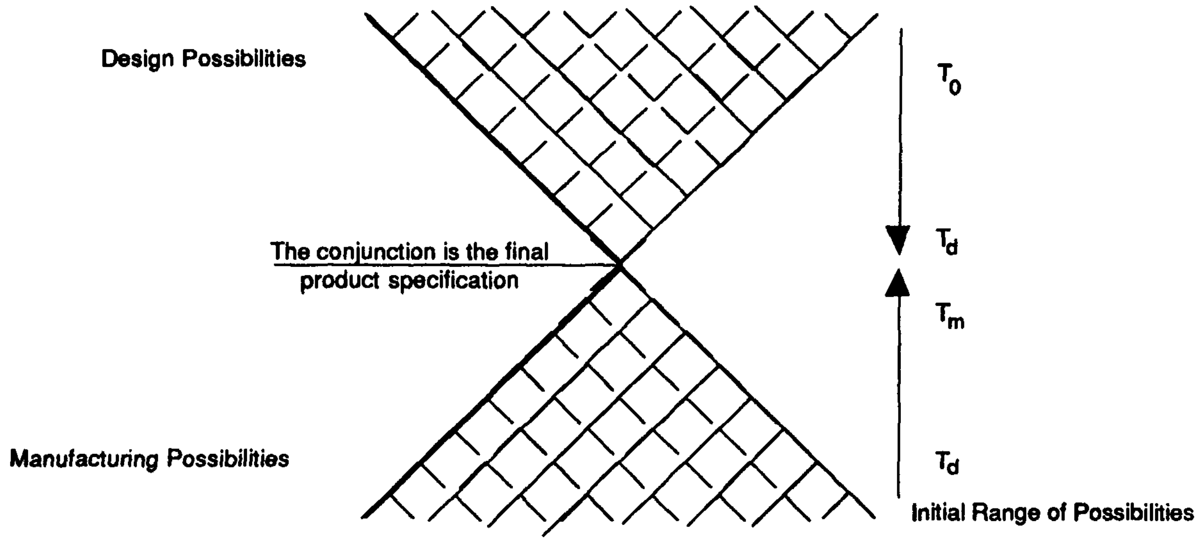


Figure 5

Figure 5 depicts the constraining of possibilities in design and manufacture. Constraints arise from the following factors, among others:

1. desired part functionality,
2. material properties and availability,
3. machine tool properties,
4. cutting tool properties,
5. setup requirements,
6. cutting parameters (speed, feed, etc.),
7. cost,
8. tolerance specifications, and
9. manufacturing processes.

Within the traditional approach to product development, the possibility trees for design and manufacture are pruned until a final specification is determined. However, given the serial nature of the effort, the narrowing of design is begun at $T_0$ and is completed at $T_d$. Manufacturing begins at $T_d$ and narrows to $T_m$.

A parallel DFM system must provide for simultaneous or interleaved analyses of possibilities from design and manufacture. Figure 6 depicts this alternative approach. This alternative promotes cooperation among human agents and computational assistants in the generation of the evolving product specification. Each human has a possibility network in mind which is dependent on the state of the evolving product specification. In addition, computerized knowledge sources provide information and constraints to aid the humans in making choices which narrow the possibilities. Prior research in cooperating heterogeneous agents for distributed artificial intelligence [Rochowiak and Interrante 1991] employed this idea.

Paramount to the success of such an arrangement is the ability of the system to dynamically adjust the focus of attention during DFM analysis.

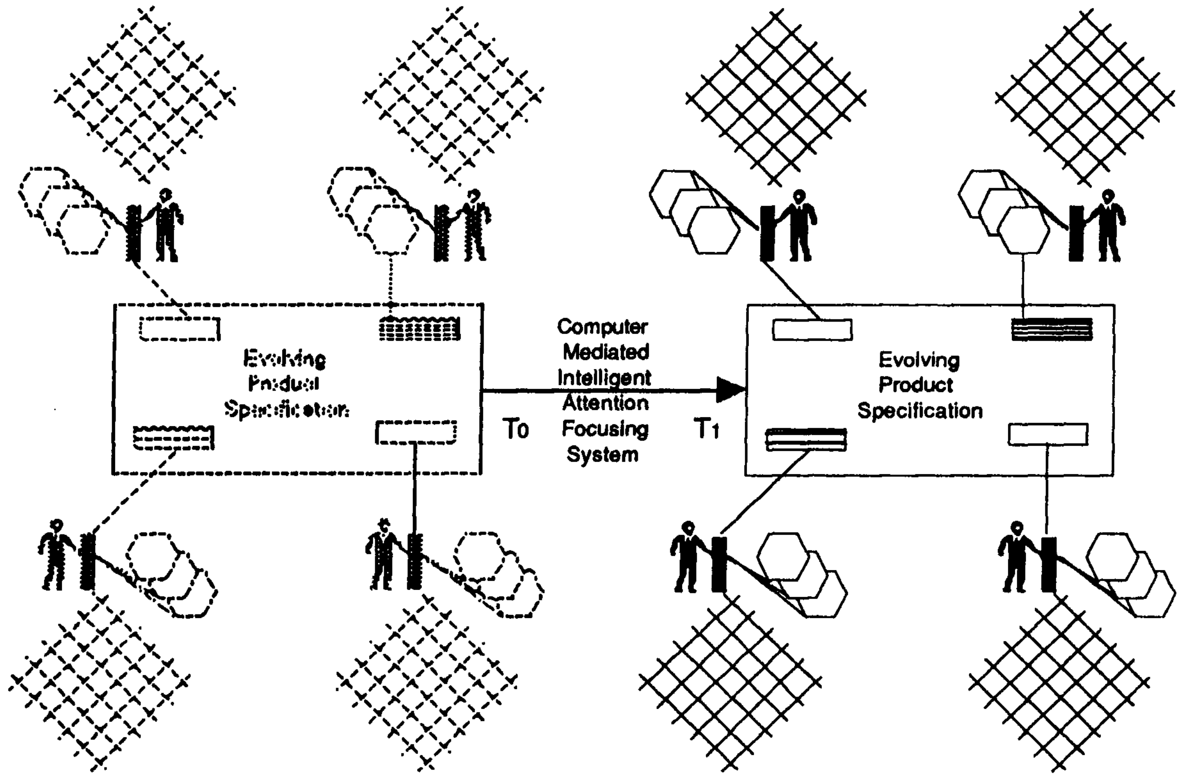


Figure 6

To conclude the beam design example, once the cross-sectional shape has been determined, the type of prestressed concrete must be chosen and the cost must be adjusted accordingly. The following choices must be made:

1. 270K prestress versus 250K prestress
2. strand diameter (with appropriate constraints given by manufacturing)
3. vertical spacing of strands
4. horizontal spacing of strands

### 4.3 Intelligent Systems Support: Focus of Attention

One of the key aspects of DFM is the vast body of information needed to accomplish analysis. An AI tool which enhances concurrent engineering must assist the human participants by providing the right information; data overload must be avoided. A focus of attention agent can accomplish this task by selecting the relevant data from the given state in the evolving product design.

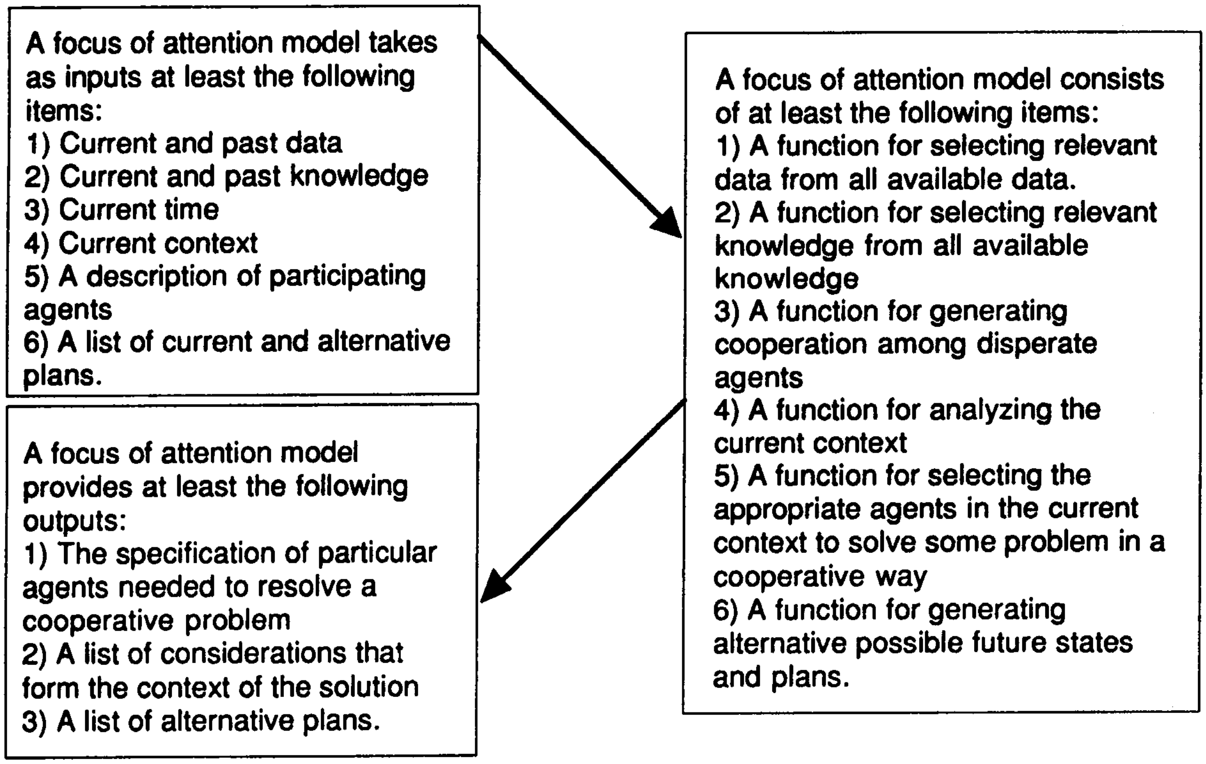


Figure 7

The focus of attention model builds on the concepts of concurrency and integration. There is access to common data, and interfaces between team members. To this is added the concept of shared knowledge and a focusing of attention. Shared knowledge allows for the focusing of attention on particular issues and makes available the data related to the decisions that are to be made. The flow of information is, therefore, neither chaotic nor overwhelming, but allows for flexibility in both information access and decision making. Figure 7 further specifies the attributes of the focus of attention model. The focus of attention capability is dependent upon knowledge information flows for various product types. Given this general body of knowledge, the system can react appropriately to a particular set of initial specifications such as load and span length in the beam example, by providing the relevant expert systems, object-based simulations, and database information. The focus of attention model provides the structure for such reasoning, whereas the initial specifications provide the trigger for determination of the pattern of inference for a given product development analysis.

An intelligent DFM system consists of agents, some of which are human, that specialize in solving particular types of problems. The DFM system also consists of knowledge sources and data sources, as in Figure 8. Without a focus of attention, many knowledge and data sources are available to the agent, but the path through the tangle is not clear. Neither the system nor the human agent can determine which agents need which knowledge and information. As a result there is little opportunity for cooperation. With a focus of attention, specific knowledge sources and data sources are made available to the agent. The path through the tangle is clear; the system allows cooperation among agents. The complexity of the situation becomes greater as time proceeds. Various links are broken and new links are added to reflect the evolving product specification. Prior research on focus of attention [Interrante 1990; Interrante 1991] has illustrated this point.

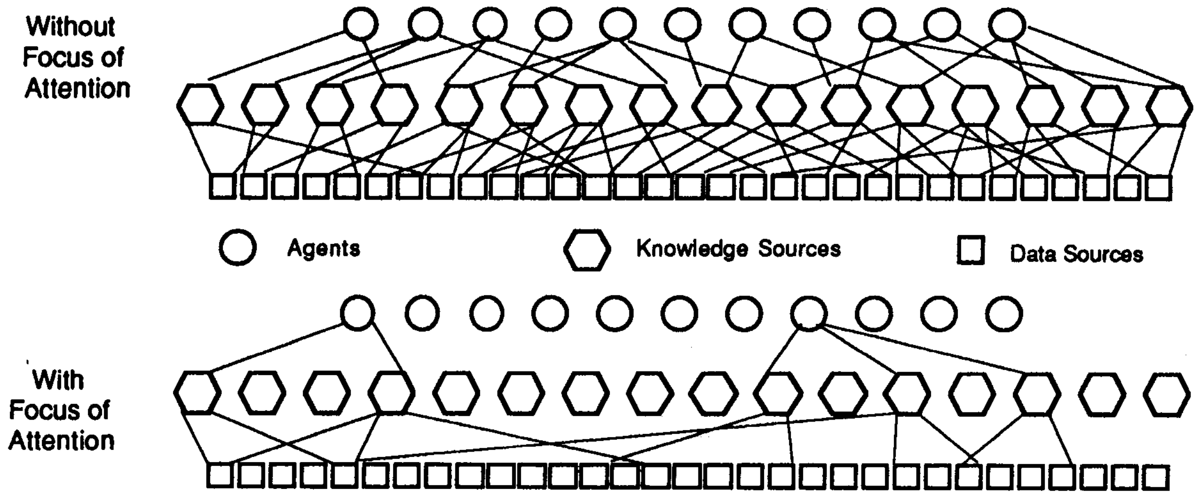


Figure 8

In the beam design example, data sources include material and cost information. Knowledge sources include prioritization of materials given the initial specifications and determination of choices available for types of prestressed concrete. The links from initial specifications to choice of material to CAD development with cost data would be dynamically created by the focus of attention agent during analysis.

## 6.0 Current Effort: Communication in Scheduling and Design in the Factory

This section describes research being performed on site and in cooperation with Chrysler Acustar, Inc. in Huntsville, Alabama. The research is supported by an grant from NSF. The Acustar factory has fifteen process lines at the plant produce 50,000 electronic and electro-mechanical parts per day. The material handling system includes a six-aisle miniload AS/RS system with two dedicated AGVs. The primary AGV system consists of 18 vehicles with 144 pick-up and delivery stations. A secondary AGV system with eight units delivers full containers from the process lines to the shipping dock. The existing material handling control system provides real-time control for more than 5000 part numbers.

Our goal is to employ both artificial intelligence (AI) and operations research (OR) techniques in the context of human communications to provide dynamic control of AGVs in response to current shop floor situation. Additional research is beginning on the development of techniques and communication paths for the design and experimentation on new lines. Although the basic research concerns scheduling, we see many similarities between the cooperative design of a schedule and other sorts of design efforts. The key mechanism is selective attention: the ability to intelligently direct the reasoning focus in order to dynamically respond to changing events in monitoring a physical system. This mechanism is designed to encapsulate and facilitate as far as possible the types of communication that would occur among human agents who address these problems. Selective attention is both reactive and proactive in nature. It forms the basis of a tightly integrated feedback loop between the current state of the physical system and the reasoning processes used to monitor and control the physical system. Selective attention provides a temporal reasoner with two types of knowledge:

1. identification of critical or significant data at a given point in time, and
2. identification of the points in time (in the immediate future) which are critical for accessing sensor data.

We are addressing the following issues in this research:

1. Sensor-based monitoring of shop floor state. This requires an adequate computer description of the plant and its interacting subsystems, such as material handling, process lines, receiving, shipping, maintenance, etc.
2. Assessment of the current state in such a way that the appropriate AGV control strategy can be chosen. This requires the incorporation of knowledge of empirical results which determine which AGV strategies for both dispatch and routing work well for given shop floor conditions. In addition, the changing of strategies in mid-production must be efficiently accomplished to maintain progress toward meeting master production goals.
3. The blending of AI and OR technologies to achieve global production goals. The meeting of these goals requires the effective use of limited resources under constraints. The use of AI techniques alone, while effective for such tasks as constraint propagation and domain description, fails to incorporate the results of years of mathematical development invested in OR techniques for manufacturing. On the other hand, the use of OR techniques alone can be too limiting in assumptions and may fail to be flexible enough to reflect actual shop floor conditions. By incorporating both types of analyses, the strengths of each can overcome inherent weaknesses of the other.
4. An understanding of interacting manufacturing subsystems. It is desired to effectively control the whole system rather than optimize small portions of the system in an uncoordinated fashion. The manufacturing floor is a large system with many interacting components. The material handling subsystem is not an end unto itself. The effect of material handling control

decisions on other manufacturing subsystems (e.g., inventory, shipping, etc.) must be modeled and incorporated into the global assessment of the impact on the master production schedule.

These four points highlight the need for cooperation and the role of human communication in the on going scheduling process. This cooperation and communication requires a great deal of human interaction. As we move forward in our analysis of the design of lines and in the experimentation on the lines in response to new products, the interactions between design and manufacture will become ever more critical. This interaction is of concern to both the design of the production line and the design of the parts to be manufactured. It is the collective set of interactions that are most telling to the success of the company's efforts.

## 7.0 Benefits: Creativity through Knowledge and Cooperation

We believe that the integration of artificial intelligence systems within a context of human communication can lead to significant benefits in design for manufacture. These benefits include:

- systems modeling of information flow provides knowledge for focus of attention
- humans and AI modules work together in cooperation
- the right knowledge is made available to problem-solving agents, including human participants
- communication problems are reduced while simultaneously providing a large number of communication links to sources of information

The benefits of our approach to DFM system are most obvious in the modeling, representation and implementation of the exchange of information which occurs during parallel DFM analysis. The systems modeling will help to effectively reduce design-to-manufacture time and increase quality and cost effectiveness. The cooperative atmosphere, in which humans apply their creativity and the computer tracks details and provides information, will also benefit the DFM process. Provision of the right knowledge to the appropriate problem-solving agents, including human participants, at the right time will allow for more informed decision making and reduce data overload. Finally, we believe that this person-centered approach can be applied to a wide variety of design problems.

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