CONCURRENT ENGINEERING: Research and Applications

CE4: Concurrent Engineering of Product, Process, Facility, and Organization

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Abstract: We argue in this paper that Concurrent Engineering of Product, Process, Facility, and Organization (CE4) is now both possible and beneficial. As quality has started to become a commodity, time to market has become the major issue for many kinds of businesses. In some industries such as semiconductors in which product and process development have become rapid and competitive, developing the factory and bringing it on-line have started to become bottleneck steps in the product development cycle. CE4 extends the tradition of concurrent engineering of product and manufacturing process: it is now possible to start to design the product, manufacturing process, manufacturing facility, and the managing organization simultaneously. Like traditional concurrent design of product and manufacturing process (CE2), CE4 probably depends primarily on setting the management objective and providing the management support. However, CE4 can build on a number of technical foundations: symbolic product and process models; support for extensive coordination among design professionals doing product, process, facility, and organization design; and analytical tools to allow designers to do what-if studies of their individual land integrated designs. Engineers now routinely use some of these analytical tools, such as simulation models of devices, processes, buildings, and facilities. We suggest adding organizational analysis tools, integrating all of these tools, and using them concurrently We suggest that benefits of CE4 will include significantly improved time to market and potentially improved product cost and quality.

Key Words: concurrent engineering, product model, process model, facility, organization, CE4 and symbolic model.

1. Introduction

Traditionally, concurrent engineering has focused on the design of a product and its manufacturing process [1]. In many industries, time to market for a new product depends increasingly on the time to develop the factory and the time to manage the concurrent engineering of the product, process, factory, and organization. In recent years, for example, management techniques and computer-based semiconductor device prototyping tools have together dramatically accelerated the process of designing microprocessors. Emerging prototyping tools, such as the Virtual Factory [2] are also starting to impact the time to design manufacturing processes in the semiconductor industry. In contrast, time to design, build, and start up a new or reconfigured factory is significant and has been difficult to shorten. As virtual product design and process tools improve, the factory-design-build-start-up bottleneck will become the greatest opportunity to reduce the critical path duration in time to market of many advanced products.

Semiconductor producers and many other manufacturers face the challenge of deriving competitive advantage from new product and process technology in shorter and shorter cycles. As shown in Figure 1, to shorten time to market for new products, producers have to "decrease the time to prototype and refine new process flows and circuits" [3]. To minimize time to high volume production, they also make the design and development of the semiconductor production facility concurrent with product and process design. At some point, they have to freeze the semiconductor design so that they can order manufacturing process equipment. To expedite factory availability, they start factory construction before the product design freeze. Because manufacturing process equipment now evolves rapidly, a technology obsolescence gap emerges in the time between order of process equipment and time that high-volume production starts. During this gap, it becomes increasingly expensive to change the process and factory design to take advantage of

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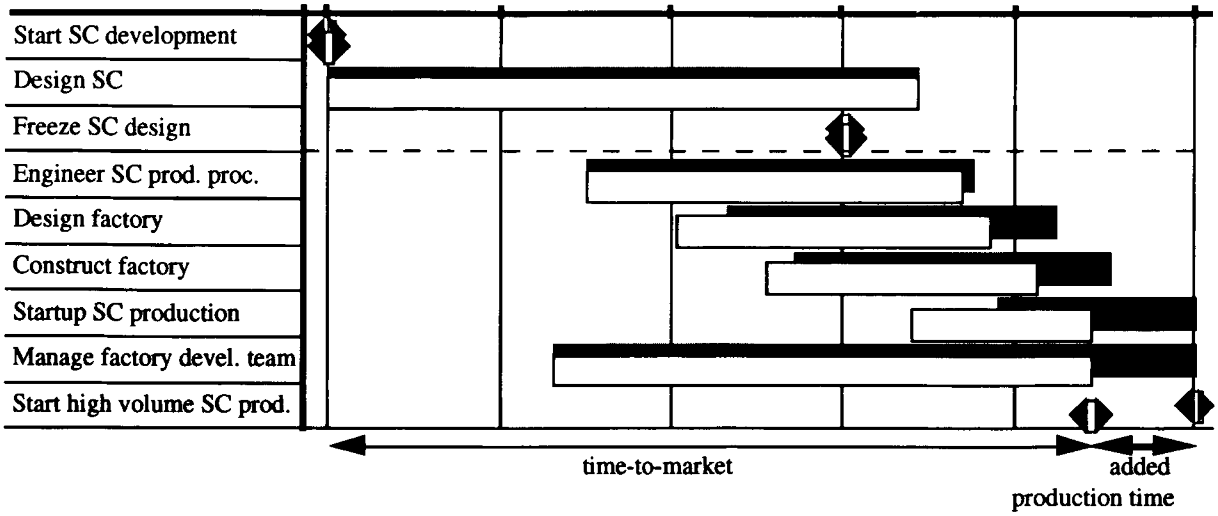

Figure 1. Master schedule for semiconductor (SC) development. Key issues for competitive industries such as electronics include (1) the time to market and (2) the technology obsolescence gap caused by the time between freezing design and full production. The shaded activities show current practice. The white activites have shortened durations as Virtual Rapid Prototyping tools allow increased concurrency, reduction in activity durations, and shortened time to market.

improved process equipment. Thus, to sell the best possible microprocessor as early as possible for as long as possible, semiconductor firms have two competing goals: (1) to shorten time to market (e.g., by early commitment to process equipment. and (2) to reduce the technology obsolescence gap (e.g., by late commitment to process equipment).

1.1 Industry Example

When a new verison of a product is designed, a semiconductor manufacturer often chooses to retrofit an existing manufacturing factory (called a "fab"). Consider a hypothetical example. A semiconductor manufacturer modifies the design of a chip. Designers decide that new stepper machines will be required to support the manufacturing, and the new steppers require slightly different mechanical and process equipment support than is present in the existing fab. This option requires the shutdown of the fab and results in a temporary, but significant loss of production. However, if the chip design is modified slightly, existing steppers could be used, and the fab process could be modified without shutdown. The costs of the second option include reduced product performance and prolonged design time. In any case, the company needs to assemble a product development team to manage the design of the chip, the manufacturing process, the fab retrofit design and construction, and the start up of the modified fab. Specialists need to join the project according to a schedule and receive realistic milestones and appropriate design and coordination resources. Today, product development trade-offs are addressed in a sequential, staged design process by engineers and managers who have limited support from analytical tools. The sequential design process fixes product and manufacturing process design before initiating factory design, and organization design is usually considered as a given.

In summary, a new product design allows manufacturing process options. The selected process allows equipment layout options. Process and layout specifications allow factory design and construction schedule options. All these options impact need of the organization for skills, budget, time, and supporting resources.

The company needs to consider a number of issues concerning the retrofit project:

- *Facility design:* should the new section of the fab be a "clean room" or use "clean machines?" The former provides a large, expensive, open space that promotes efficient manufacture but that forces future fab shutdown for subsequent retrofit. The latter provides markedly less expensive construction, but potentially less efficient operation.
- *Organization:* whom should the manufacturer hire? Should engineering services be contracted or provided in-house? Should engineers and a general contractor be hired separately, or should an integrated "design-build" firm be hired? Who from the product and process design team should coodinate with the factory development team, and when should their coordination be scheduled? What information should the product, process, factory teams exchange? Who is on the factory start-up team; when should this team start work; and when should it disband?
- *Product and process design:* Can they be modified to enhance time to design or start up the factory? Can they be mdoified to support future product, process or factory design changes?
- *Factory construction management:* Can construction be

phased to allow incremental operational start-up? Can some building subsystems be specified and ordered early, prefabricated and installed quickly, or should they be fabricated on site?

1.2 CE4 Objectives

To support concurrent analysis of these trade-offs, we are using standard product design tools and building project modeling and analysis tools. They support integrated computational virtual prototypes of:

- process design
- factory design, construction, and start-up and operation processes
- engineering organizations that do product, process, and factory development

These models will allow manufacturing firms to analyze their development process and manage the degree of overlap of virtually all these processes. They can analyze as early and for as long as they wish to gain insight into technical, organizational, and economic trade-offs associated with a particular project. Based on these virtual product, process, facility, and organization models, multidisciplinary simulations will elucidate the risks of delaying decisions or increasing concurrency and suggest organizations and processes best suited for the successful development of a new production facility. The models will help identify opportunity for local de-optimization, e.g., of factory design time, to facilitate global optimization, e.g., of time to market. An analyst will use the virtual prototype model to understand and perform trade-off studies to optimize the global time to market objective.

2. Background

Traditionally, design of each project entity (e.g., the product, the facility construction organization) takes place using traditional methods of defining function, synthesizing form, evaluating behavior, and iterating on the design process. Each of these designs is sequential, and each design considers only itself, not the evolving designs of related entities. In contrast, we use Virtual Prototype Modeling to support concurrent engineering of a product, its manufacturing process, a manufacturing facility, its construction and operation, and the overall project management organization (see Figure 2). Whether a project is successful with respect to typical project objectives (time, cost, quality) depends on aligning the scope of the project with its delivery process and organization. Simulating this product-process-organization (PPO) interaction to evaluate the goodness of a particular delivery schedule, organization structure, or project design is the key motivation for extending concurrent engineering into the directions described in this paper. We anticipate that such PPO models will lead to more successful projects.

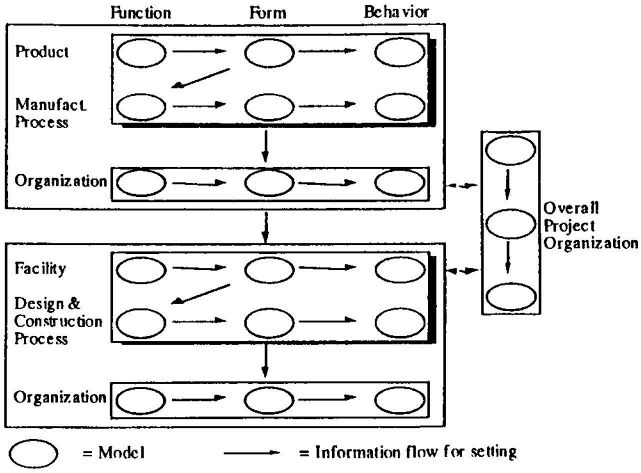

Figure 2. CE4 extends the scope of traditional concurrent engineering of product and manufacturing process (CE2) to concurrent engineering of product, process, facility, and organization (CE4). CE4 also provides tools and methods to design and analyze this extended scope. The uppermost Product and Manufacturing Process rectangle shows CE2. CE4 encompasses all entities in the figure.

This section discusses CE2 technology and Section 3 discusses the emerging components of the extended virtual model, and introduces VDT to analyze organizational designs.

2.1 Concurrent Engineering and Rapid Prototyping

Research on concurrent engineering so far has concentrated on developing shareable product and production process models and communication infrastructure for designers. These models represent different design perspectives and help designers to collaborate with each other through data sharing and structured and nonstructured communication [4]. Initially, concurrent engineering has focused on the practical aspects of "coordinated design of products and processes" and do not model organizations that carry out these processes as separate models [1]. Many researchers have developed computer tools in support of concurrent engineering.

Designworld, for example, is an integrated engineering system for digital circuits that supports various phases of the life cycle of an engineering artifact [5]. Designworld uses an engineering knowledge representation language called KIF (Knowledge Interchange Format) and a protocol called KQML (Knowledge Query and Manipulation Language) to support inter-agent communication and to integrate various tools with heterogeneous perspectives. Designworld's major features are (1) a machine-readable knowledge-level representation of all product information, (2) automated analysis at various phases of the development process, and (3) automated solution of routine tasks in engineering. Our work addresses a different set of engineering issues than those on which Designworld focused, and the concurrent engineering model includes a significant additional factory and organization focus.

PACT is an experimental test-bed for the integration of heterogeneous knowledge-based engineering tools to design a single electromechanical device [6]. PACT demonstrates a flexible federation architecture to support concurrent engineering. It avoids the inflexibility and the lack of expandability of centralized database approaches by means of a shared communication protocol and a shared ontology. Thus, a new tool can easily be added to the collaboration without substantial modifications. PACT however, does not address coordination issues for a concurrent engineering team.

Next-Cut is a concurrent product/process design system for mechanical engineering [7]. The basic idea behind Next-Cut is to do as much process planning as possible while the design evolves; and to provide user interfaces that encourage the designer to explore manufacturing issues. Using Next-Cut, different specialists, and tools can engineer the manufacturing processes while the design takes shape, instead of afterwards. Next-Cut can also work with partially specified designs so that it can support the early product development phases. Next-Cut demonstrates concurrent engineering of manufacturing products and process, but does not include the design, construction, and start-up of the manufacturing facility itself.

DICE is a Distributed and Integrated environment for Computer-aided Engineering developed at MIT [8]. DICE is a network of computers and users. It supports communication and coordination through a global database and a control mechanism. DICE includes a blackboard to store data and facilitate communications, knowledge modules to solve particular problems, a mechanism that evaluates implications of actions taken by knowledge modules, and a facility to propagate changes and assist in the negotiation between knowledge modules. DICE demonstrated that an object-oriented and knowledge-based computer environment can be established to overcome the shortfalls of "over the wall engineering." At its current stage, DICE does not take into consideration the issues involved in design of the facility delivery process and the design of human organizations.

2.2 Product Modeling

Communication between design and construction professionals can be improved by integrating applications used by these professionals. Most commonly-used means for sharing information among professionals, e.g., CAD files, do not provide sufficient information about a product to enable applications integration. Applications need to represent and share information with explicitly defined meaning, that is semantic information about the complete product design. Symbolic product and process models can support such applications integration.

In the seventies and eighties, CAD systems became the central points for integration and thus for standardization. Models for the exchange of shape information grew more and more sophisticated, from wire frames and surface models, via solid models, to relational reference models. Nevertheless, integration systems that use topology and/or geometry as kernels have had limited flexibility because:

- The shape of a product is not stable during design.
- Often, information about a product or facility already exists before a shape is chosen.
- Different participants in the project often use different shape representations.

Therefore, geometric modeling evolved to semantic product-modeling to represent product features and some relationships among features such as adjacency and connectivity, in addition to dimensions. Product modeling provides high-level, computer-interpretable communication because it stores and communicates the *definition* of a product rather than its *geometric representation* (as in a CAD model) or *presentation* (as in a paper drawing). The definition of a product is often new characterized by its function (or design intent), form (or shape, material, and topological relations), and behavior [9]. The definition of a product and the language in which this definition is exchanged have to be agreed upon by the participants in a project. The product-model contains information for all life cycle stages and for all participants in the building process. From the (neutral) definition, participants can derive the information and the representations they need. Geometric information is no longer the core, but one of many properties. Traditional documents, such as drawings, can ultimately be derived automatically from the product-model.

Recent research suggests the potential of semantic, computer-interpretable models. Examples include the RATAS building model [10], EDM [11], IBDE [12], DICE [8], ICADS [13], and SME [14]. All of these prototypes support design based on a semantic representation of project information.

The major product-modeling standardization effort today is ISO-STEP, the international STandard for Exchange of Product model data. This standard specifies a format for the unambiguous definition and exchange of computer-interpretable product information throughout the life of a product [15]. STEP includes view and application independent languages for specifying information structures—EXPRESS—and exchanging information—STEP physical file format and STEP Data Access Interface. ISO-STEP is supported by many ongoing or recently completed research projects in product modeling, in particular, those sponsored by the European Union, e.g., COMBINE [16], ATLAS [17], CIMSteel [18].

Until recently, product, process, and resource information were modeled separately, e.g., by using the STEP product modeling approach and the IDEF0 process analysis method [19]. With CE4 modeling, we want to integrate the three types of information in one, logically unified model, extending the work of e.g., Björk [20], Froese [21], and Luiten [22]. Our approach is the same as in product modeling: to represent information in semantic, computer-interpretable models. These unified product, process, facility, and organization models enable semantic reasoning and communication between applications that support product design, production process design, facility design, facility construction management, construction, start-up, and organization design.

3. Virtual Project Model Components

Our work builds on three intuitions. First, for complex products such as semiconductors and pharmaceuticals, concurrent engineering can and should broaden its focus to consider coordinated design of the production factory as well as the product and manufacturing process. Second, it is possible and valuable to analyze and design the organization that conducts the concurrent engineering. Third, the most promising way to support concurrent engineering of organizations and systems is to develop integrated symbolic models of products, design and manufacturing processes, and organizations. As shown in Figure 3, we have implemented initial versions of such symbolic models as Virtual Prototype Models. Section 4 provides examples of the classes, objects, and attributes used to describe the PPO model.

3.1 Organizational Modeling: The Virtual Design Team (VDT)

To use new technologies like concurrent engineering and rapid prototyping, organizations have started to re-engineer themselves to adapt their information flows and decision-making processes to exploit capabilities of new technology. Organization theory provides only general guidelines about how to structure an organization and support it with technology. We have developed the VDT computational microlevel organization model to analyze predicted organization behavior at a sufficient level of detail as to enable systematic organizational design [34].

We have carefully considered the reasons to include organizational modeling in our work. Experience has demonstrated that organizational issues, not technology per se, frequently limit the business effectiveness of new technology. The organization needs appropriate training, effective coordination, and control mechanisms to move data accurately and quickly from its source to *all* relevant decision-makers, and appropriate communication and coordination tools. The organization needs to match important development activities with appropriately trained groups who have appropriate review and decision authority. Ettlie and Reza [23] make the case for considering organization. They claim that "new hierarchical structure, increased coordination between design and manufacturing, and greater supplier cooperation . . . positively affect the productivity of new manufacturing systems. . ."

The ongoing Virtual Design Team (VDT) project has created software modeling and simulation tools to predict changes in the duration, cost and quality of a design task, given a description of the organization performing the design, the capabilities of the organizational participants, the design task specification, and the communication and coordination tools. To date, it has focused on the design phase of capital projects. The VDT model represents attention allocation and routine and exceptional informational processing by organizational subteams. The VDT system simulates the behavior of the organization to predict the performance of the overall team as subteams perform their planned activities. The VDT organizational modeling process allows the owner of a product to align its organization with the product and process design, and with the factory design and its development and start-up processes.

3.2 SC Production Process Planning: Virtual Factory

Software tools can be used to help design semiconductor fabrication processes. Such fabrication process plans lead to

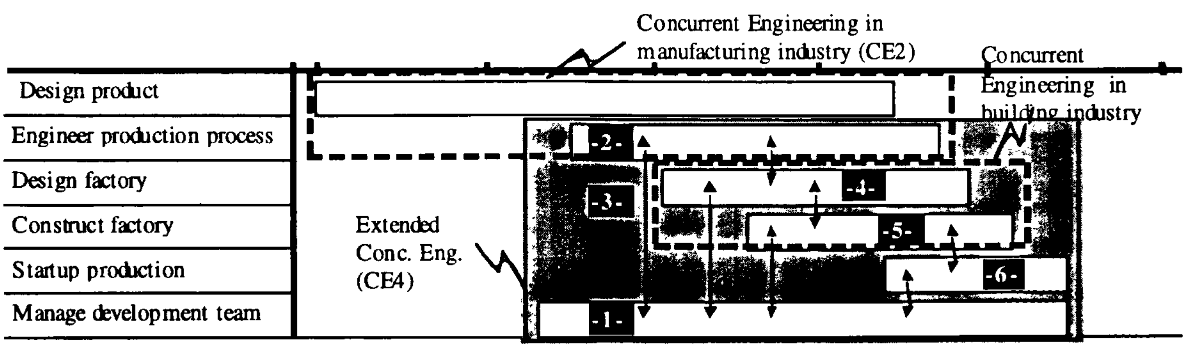

Figure 3. The numbers refer to the subsections below that describe the specific problem area and approaches in more detail. The Virtual Project Model integrates: 1. Organizational modeling and simulation (VDT), 2. Virtual Factory, 3. Desktop Engineering, 4. Semantic CAD modeling, 5. Automated construction process planning (OARPLAN, MOCA), and 6. Automated plant diagnosis (IRTMM).

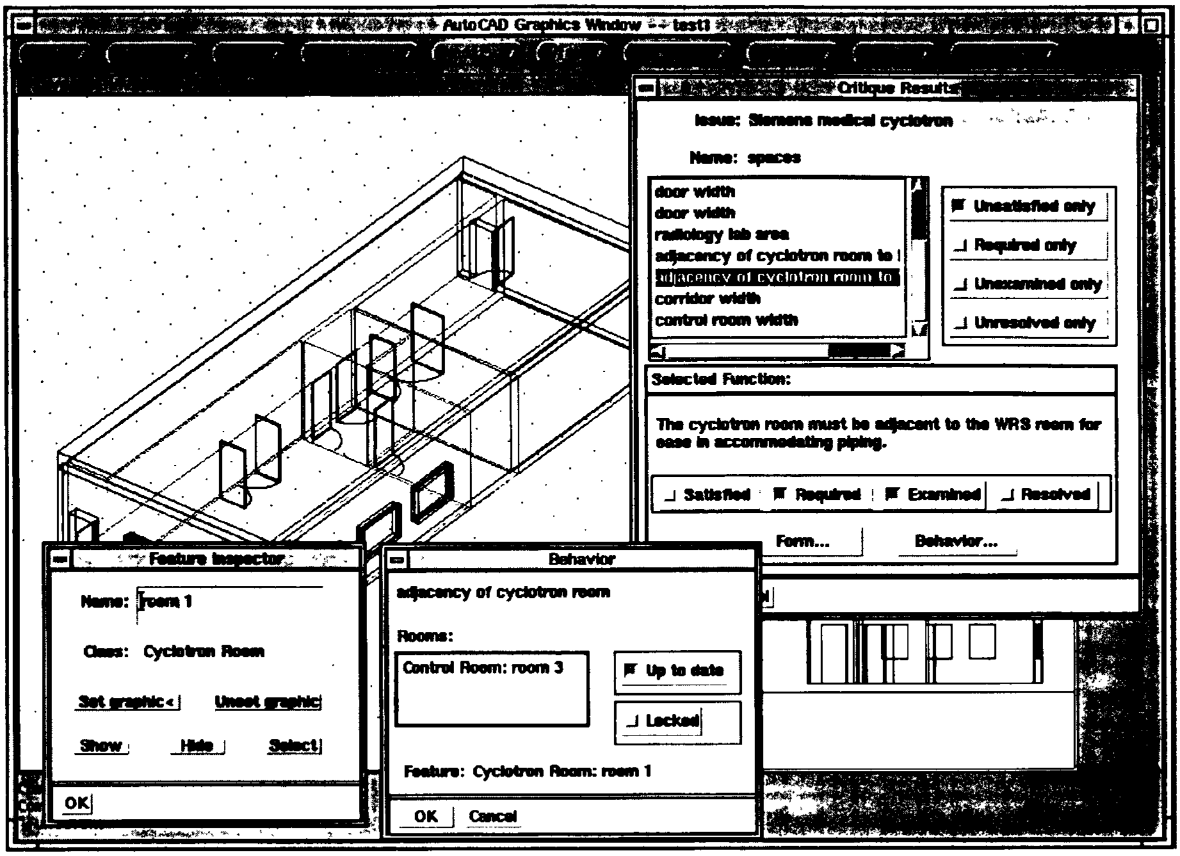

Figure 4. In the SME system, concurrent design involves analysis of symbolic models of designs that normally exist, at least in part, in graphic form. SME then critiques the building design as described in the associated symbolic model. SME allows the user to define and relate both graphic and symbolic objects as needed.

requirements for fabrication equipment and hence to fab space and support systems.

The Virtual Factory [3] consists of a hierarchy of models including equipment, processes, devices, and circuits to describe the chips that are built in the factory. It also includes a set of factory cost and performance models that describe certain behaviors of the factory itself. To the extent that these models represent reality, the Vitual Factory can be used to design manufacturing processes, to assess the manufacturability of a product, to optimize factory throughput, and to predict delivery times of products. The Virtual Factory provides the same capability for the process designer and the plant manager that today's CAD tools provide for the circuit designer. The same productivity enhancements that have occurred in the chip design area through these tools should be possible in the manufacturing area. The Programmable Factory [2] is an actual flexible computer-controlled manufacturing facility for semiconductors that is modeled in the Virtual Factory. The Virtual Factory represents the design of manufacturing processes, and it can assess the effectiveness of a given process. Thus, it provides a capability for the process designer that is similar to that provided to the product designer by CAD and analysis tools.

3.3 Semantic CAD: SME

Most commercial CAD systems store very little content with their graphical primitives. Clayton et al. [14] extended standard CAD to allow semantic annotation. Called Semantic Modeling Extension (SME), it allows a designer to use CAD in a traditional way to describe the graphic form of a facility. After creating a CAD drawing, the designer then annotates graphic elements with their intended functions, i.e., their semantic content, in creating a symbolic model of the facility being built. The symbolic model represents both the geometric form and the intended function of the design within a particular context, e.g., requirements for egress. Figure 4 shows an example CAD drawing and part of the SME user interface that is linked to the symbolic model. A design typically has many graphic elements and functions. As the design model now represents both the geometry and the semantics, knowledge-based and algorithmic critiquing tools may be used to evaluate the sufficiency of the design behavior with respect to the design functional intent. The SME system has been demonstrated extensively and used in classroom teaching. Test cases modeled with SME include a university building, hospital laboratories [26], and mechanical devices [27].

3.4 Automated Construction Planning; OARPLAN and MOCA

Scheduling (often called "project management") systems normally depend on users to identify all the activities and their predecessors and successors manually. In practice, engineering and construction schedules often have 1,000-10,000 activities. Thus, manual generation of process plans in the ACE industry is a major bottleneck in providing designers with early feedback on cost and schedule implications of design decisions.

We have now successfully developed a construction planner, called OARPLAN [17], that automatically generates routine or semi-custom plans for facility design, construction, and start-up, based on symbolic product models. It has been applied successfully on full-scale construction projects: an industrial complex and a performance testing laboratory [18]. Both were structural steel facilities consisting of about 1,400 components. OARPLAN has also successfully planned repairs of two components in an operating power plant (the main boiler feed water pump and a boiler tube leak) [19].

OARPLAN attempts to attain both generality and high performance by generating project plans through reasoning about basic engineering principles and construction objects [17]. Specifically, OARPLAN represents and reasons about *Objects* to be built, construction *Actions* and construction *Resources*. Duffey and Dixon [20] report on a similar approach to schedule manufacturing processes. OARPLAN's planning knowledge includes constraints based on activity constituents and their interrelationships. In OARPLAN, the product model is a semantic model of the physical structure described in terms of topology (e.g., supported-by, enclosed-by) because many construction and assembly planning tasks and their sequences can be derived from topological relationships among objects. Exploiting the object definitions and engineering constraints among them, the planner can hierarchically generate required activities for achieving a given goal and order these activities in the way that constructively satisfies the constraints. It is important to note that OARPLAN infers an action's preconditions and effects as it examines associated constraints. The user does not specifiy them. By interring activities and their precedence, OARPLAN extends classic STRIPS-style planners.

While topological relationships are important to consider when planning and scheduling construction and maintenance work, explicit method and resource models are needed to produce realistic plans. Such resource models add an economic perspective to schedules and break down the work into manageable activities. The Model-Based Constructability Analysis System (MOCA) complements OARPLAN with models of such methods. It plans, schedules, and estimates the construction of concrete structures [21]. Figure 5 suggests the interactions between factory design and the factory construction plan and schedule. With tools such as MOCA, the product and process designers can assess the effects on the complete product delivery cycle of changes in their designs or of construction issues such as resource availability.

These tools demonstrate that it is possible to automate the generation of process plans based on product and method models for building projects. These process models also

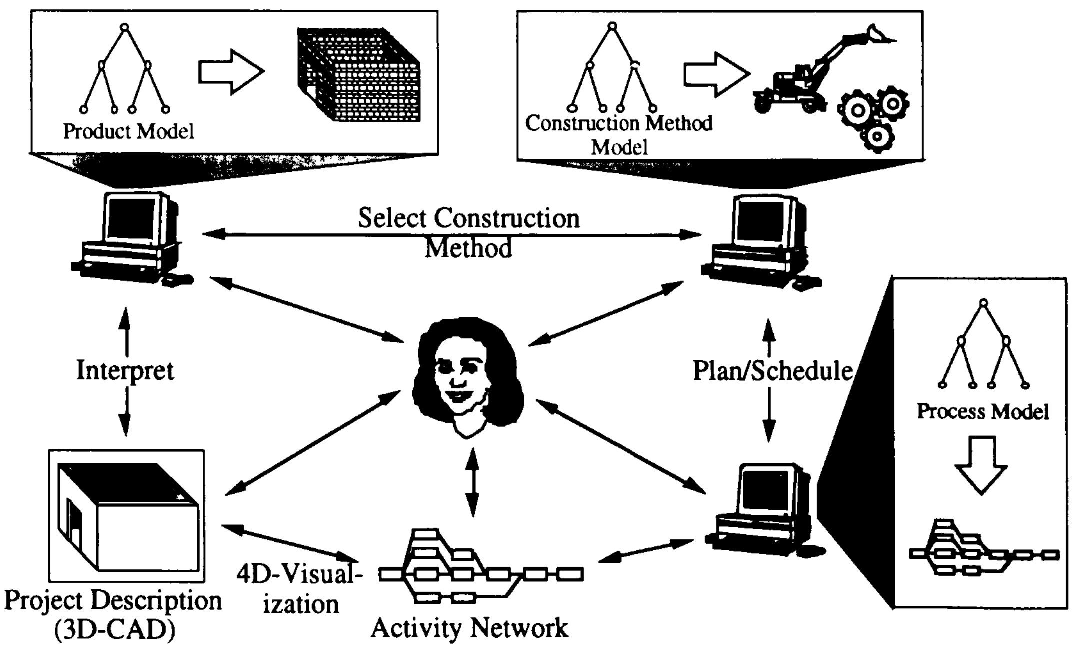

Figure 5. Symbolic and graphical facility product, construction method, and construction process models support the selection of construction methods and design of activity network alternatives. These construction management designs are done concurrently with factory design alternatives in CE4.

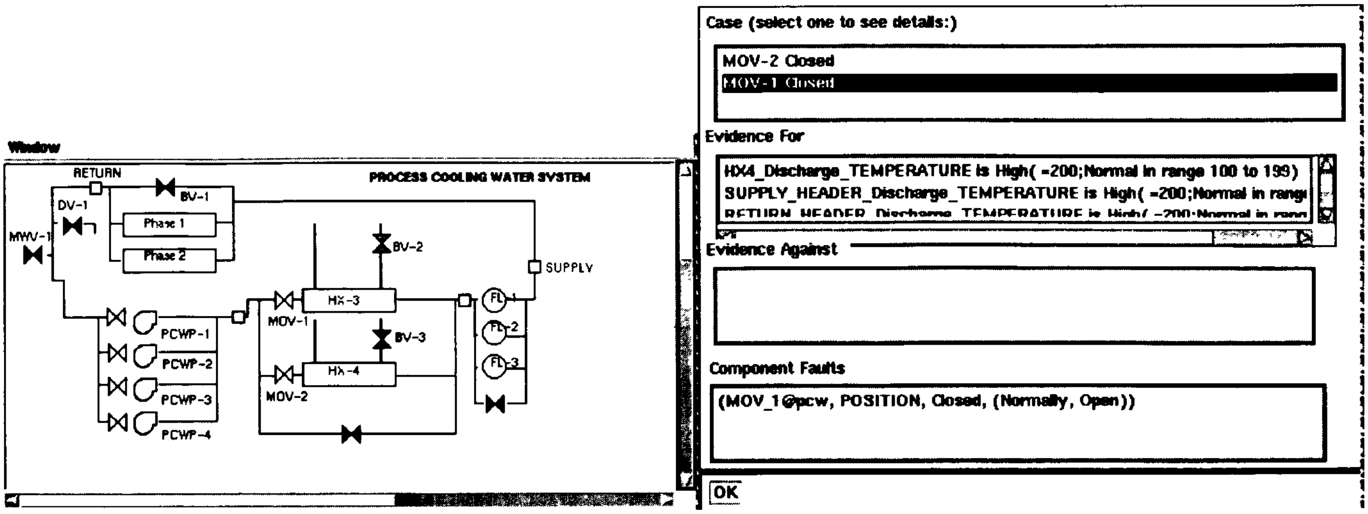

Figure 6. Example of virtual product model and its use in diagnosis. The left figure shows an active P&ID for the Process Chilled Water subsystem in a semiconductor fab. A user gets component status information by selecting any component icon with a mouse. The right panel shows the candidate causes and potential effects of an actual problem that arose during start-up. The virtual product model shows that the particular problem can occur, but that the control and monitoring system can detect it promptly.

link facility development with the organizations in charge of their design and construction.

3.5 Equipment Diagnosis: IRTMM

Software tools analyze the behavior of facility support systems. These tools help both design and facility start-up teams. The Intelligent Real-time Maintenance Management (IRTMM) system was designed to aid maintenance management for power plants [19]. This project developed and tested theories and systems with which power plant owners can plan maintenance when needed for engineering and business needs, rather than by an arbitrary schedule or following breakdown. This project has demonstrated a prototype system architecture that integrates software modules around a symbolic, logical plant model. The integrated system allows engineers and owners to analyze both the technical and business aspects of decisions regarding maintenance planning.

The maintenance management project (IRTMM) has four principal components:

- *Plant Model:* A symbolic model of the components, systems, parameters of a plant, including their connectivity, intended functions, and potential (qualitative) behaviors. We built the plant model manually by interpreting the Process and Instrumentation Diagram (P&ID), a standard engineering representation of facility systems (see left half of Figure 6).
- *Situation Assessment (SA):* Diagnoses plant equipment problems (see right half of Figure 6).
- *Planner:* Plans equipment repair.
- *Value Analysis:* Assesses net value of maintenance jobs.

The plant model and SA together provide a uniform environment to describe the fab support systems, including components, their behavior, intended functions and connectivity. The virtual plant model supports design, start-up planning, and later both start-up and operations.

3.6 Desktop Engineering

Our software tools and those of others are starting to have the ability to analyze proposed organizations and facility designs, construction plans, and start-up processes. These analysis tools use simulation to generate the predicted behaviors of organizations and systems, including costs, durations, egress, energy use, coordination loads, and resources required. Users of such desktop engineering analysis tools then compare predicted behaviors with intended functions to diagnose problems from the perspective of various engineering disciplines. Powerful and inexpensive computers enable the movement to desktop engineering [24].

Our research, and that of others, e.g., Fenves [12], suggests the possibility of using desktop engineering tools in engineering practice [25]. Desktop engineering will have similarities with the current practice of desktop publishing. Desktop publishing now supports the entire writing process, from initial note taking to final preparation. Using integrated desktop engineering tools, a single specialist or small team will develop a design concept. Effective and well-integrated suites of CAx applications enable this movement. The small development team will consider the suggestions from multiple computer-based critiquing systems in developing an initial concept. As necessary, the desktop engineer will send design versions electronically to human engineering consultants for their review and suggestions. We have started to use desktop engineering first in support of concurrent conceptual design.

4. Test Case

The points of integration between the product-process model and the organization model are the project activities. This section gives specific and general examples from the test case we use to ensure the practical applicability of the approach described above. It shows how activities are modeled in the system and how they link to the facility model and to the organization model.

Activities have a graphic representation as schedule activity in a CPM diagram. In addition, a graphic component representing a piece of equipment, e.g., a Slurry Blend/Mix/Distribution station, is drawn in AutoCAD at the same time that this activity is simulated in the schedule sequence. These representations are linked and given semantic meaning through symbolic activity and product models, which can be defined a priori or on the fly. Using design rules, these symbolic models then define the necessary relationships (e.g., schedule logic for individual activities).

4.1 Activity Attributes

Activities are modeled with the following basic attributes: Activity Name; Duration; Early Finish; Early Start; Geometric attributes in ACAD drawing file: (these attributes maintain the tightly coupled link between the graphic and semantic models) color, layer, location (x, y, z coordinates), name, type, scale (in x, y, z directions); Late Start; Late Finish; Number of linked activities; Predecessor Activities/Links; Successor Activities/Links.

4.2 Level of Detail of Activity Model

Definition of the appropriate levels of detail is an important step in the composition of an integrated product-process model. For example, the aggregate activity, Demolition of Piping, can been defined to include the demolition of all of the following utility lines in this particular example of a slurry system conversion project:

- water lines
- bulk gas lines
- Acid Waste Neutralization (AWN), Cyanide Destruct System (CDS) drain lines
- scrub exhaust lines
- other process utility lines

In this case, the specification that demolition must be carried out all the way back to the lateral Point of Connection (POC) valve/damper can be shown most clearly through a 4D visualization which displays the elimination of the components completely to the POC.

4.3 Activity Attributes to Support VDT

Some of the same and additional attributes are needed to link activity models to the organization model. These include:

- *Work Volume:* measure of amount of work.
- *Predecessors/Successors:* determine when an activity may start.
- *Reciprocal With:* Activities with reciprocal interdependence give rise to communications among organization actors. If these communications are ignored or lost, failure rate goes up.
- *Dependent Activities:* The dependent activities are those that get additional work when an external failure occurs.
- *Complexity:* High complexity increases processing time, low complexity reduces it.
- *Uncertainty:* High uncertainty increases communication frequency for reciprocal activities.
- *External Verification Failure Probability (VFP):* Base odds of an exception of the type that causes delays to other activities. Revised up or down at runtime.
- *Internal VFP:* global odds of an exception that only delays originator.
- *Craft Requirement:* If craft requirement fails to match skills of assigned actor, a multiplier is applied to VFP.

4.4 Organization Attributes

The following attributes model an organization and support the study of trade-offs between various organizational designs with respect to team experience, team members, and organization structure.

- *Team Experience:* High team experience reduces communication frequency for reciprocal activities.
- *List of Actors* (see Section 4.5 for specific actor attributes).
- *Centralization:* Low, medium, or high; determines probability that an exception is handled at a certain rank (PM, SL).
- *Formalization:* Low, medium, or high; determines the ratio of informal communications to formal meetings.
- *Matrix Strength:* Low, medium, or high; determines whether actors prefer to attend informal communications (high) or formal meetings.

4.5 Actor Attributes

(An actor may represent an individual employee or a team).

- who they supervise/who supervises them
- which activities they are assigned
- their "role" (Project Manager, sub-team leader or sub-team)
- proficiency at different craft (e.g., high for mechanical, medium for civil)
- *Task Experience:* Low, medium, or high; determines how long an actor has been working on this kind of work.

Table 1 . Comparison of engineering approaches: Concurrent engineering increases the scope of design options considered during design; delays the time to commitment, thereby retaining flexibility longer into the design process and enabling opportunistic response to changing market and technology; and still improves product time to market.

	Uncoupled	**CE2**	**CE4**
Scope of Design Options	**Product**	**Product, Process**	**Product, Process, Facility, Organization**
Time of commitment to design concept	Commitment to product design precedes manufacturing process, factory design	Commitment to product design, manufacturing process simultaneously; precede factory design	Simultaneous commitment to product, manufacturing process, factory design, organization design
Time to Market	Longest	Faster	Faster

5. Conclusions

We discuss virtual rapid prototyping concepts and integrated tools to support concurrent engineering of product, manufacturing process, factory, and the managing organization. We describe our initial implementation of virtual prototyping tools to help this extended concurrent engineering design process. When successful, these tools will lead to radical shortening of the time to bring new factories on line, and they will contribute significantly to reducing total time to market of products being built. Table 1 compares uncoupled sequential design practice with traditional concurrent product and manufacturing process engineering (CE2) and with concurrent engineering of product, process, facility, and organization (CE4).

There are several research and business challenges to develop effective CE4.

- Developing generic CE4 models is a research issue. Such models need to include different levels of abstraction in support of conceptual and detailed design; they need to represent the different perspectives of different engineering disciplines [22]; they need to be customized for the needs of different projects yet be standardized enough to be understandable and usable by different users over the facility lifetime; they need to be tested using reasonably general yet efficient methods.
- The STEP product modeling standard needs extension to represent design intent and support calculation of design behaviors. Practice issues include training CE4 engineers, managing the transition from current practice to CE4 while still meeting quarter-to-quarter performance and financial objectives, developing supporting software and company support sytems, validating the designs developed by CE4 vendors, and adjusting the business model so that CE4 providers can get paid for their value-adding services.
- Scale is an issue that encompasses both theory and practice. The complexity of issues in CE2 may be two to ten times greater than four-phased design. The complexity of information and management coordination for CE4 would obviously be far greater.

We will need to develop both theory and experience to identify the useful abstractions that support CE4, and we will need to develop the technical and organizational mechanisms to manage the resulting high level of complexity.

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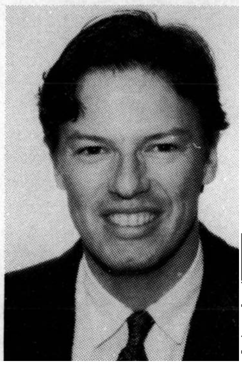
Martin Fischer



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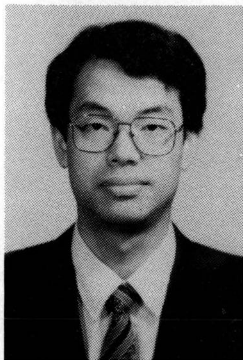
Yan Jin



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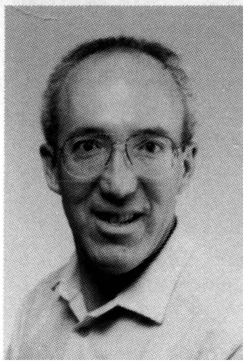
Raymond E. Levitt



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