NISTIR 5745

Product Realization Process Modeling:

A study of requirements, methods and and research issues

Kevin W. Lyons
U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Gaithersburg, MD 20899

Michael R. Duffey
Richard C. Anderson
George Washington University

NIST

NISTIR 5745

Product Realization Process Modeling:

A study of requirements, methods and and research issues

Kevin W. Lyons

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

Michael R. Duffey
Richard C. Anderson
George Washington University

June 1995

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arati Prabhakar, Director

Foreward

This report presents a bottom up view of the requirements, industry practices, and research questions which should drive new methods and computer tools for process modeling of product realization. It does not prescribe, or even discuss in detail, formal language specifications for modeling product realization processes. Comprehensive, enterprise-level models of the diverse human and machine task interactions necessary to build an electro-mechanical product are still premature. Instead, we have tried to address a wide range of industry-relevant modeling issues to help focus discussion on future research directions.

Among those we wish to thank for their consultation in this study are Daniel Mark and Drew Jones at the NASA Goddard Space Flight Center; Korhan Sevenler and Bud Krayer at the Xerox Corporation; and Amos Freedy and Azad Madni at Perceptronics, Inc.

1. Introduction

The purpose of this document is to identify and document key requirements, industry practices, and research questions which should drive new methods and computer tools for process modeling of product realization. It addresses a wide range of industry-relevant modeling issues to help focus discussion on future research directions and its intended audience are modeling researchers and practitioners in industry, universities, and other federal agencies. Although process modeling methods have been applied to many types of development efforts (e.g., software engineering, VLSI), our sole focus in this report is realization of discrete electro-mechanical products.

Manufacturing firms in the U.S. and worldwide use various types of *process models* to study their product realization processes. These models help document their understanding of current ("as is") operations and explore possible ("to be") process changes. Despite the fact that these models are relatively high-level and organizational in scope, they are attracting interest among design engineers and systems engineers. For electro-mechanical products, the complex task interactions that cross functional groups and departments profoundly impact cost, quality, reliability and time-to-market. However, they are extremely hard to visualize at early design stages. This report attempts to identify future research directions within a bottom up context of industry PRP modeling requirements.

How might new computer-based tools enhance PRP modeling? For many industrial firms, both the methodology and data in their process models have been understandably proprietary because of their competitive significance. Hence, there has been relatively little dissemination. This report presents some of the industry requirements, existing methods, and research issues for process modeling in design and manufacturing. It also suggests possible opportunities for exploring and testing new process model architectures. Observations include the following:

• Emerging PRP modeling tools are reasonably useful for *visualizing* process flow at multiple levels of abstraction. But beyond simply documenting activity precedence in an acyclic directed graph, PRP models have only very limited capabilities to characterize design iteration, support simulation for schedule and cost, and represent time-dependent information flow in the enterprise.

• In contrast with process planning paradigms in manufacturing, the accuracy and precision of PRP models are inherently limited by subjective descriptions of human tasks and task interactions. There are also significant trade-offs between clarity of the model (by limiting details of complex interactions) and the increased modeling effort required for precise output metrics.

• Meaningful research toward new PRP modeling techniques will require extensive access to real world business and technical data from diverse functional groups within commercial manufacturing organizations. Also, new mechanisms to validate research model concepts are required.

• Process models for electro-mechanical systems are inherently more difficult than for VLSI design, and probably even software design. Product complexity breeds process complexity, and the mechanical component interactions of geometry, heat, vibration, diverse fabrication constraints, etc. can make it difficult to predict process sequence beforehand. As Whitney has discussed [Whitney 94], the well-structured, top-down design processes used for VLSI design offer few useful process analogies for electro-mechanical assemblies. For the latter, many failure modes cannot be predicted by existing computer analysis tools, and are uncovered only during build/test cycles. This is particularly true for assemblies that involve vibrating elements, compressed gases, or other distributed system interactions.

Despite these caveats, research efforts in new PRP models should be encouraged because of their potential pay-off for many different applications: documentation of existing best practices, identifying bottlenecks (e.g., resource constraints) and task redundancy; "what if" analyses of design alternatives; risk assessment for schedule and cost; archiving PRP processes; training; and many others. This report attempts to identify future research directions within a bottom up context of industry PRP modeling requirements.

2. Definition of a PRP Model

The term PRP model (Product Realization Process model) will be used in this report to help reduce the ambiguity of the more generic term "process model." Definitions of "process model" which are at least partially relevant to the content of this report can be found in [Busby 93, Duffey 93, Kusiak 94, Malone 93]. For purposes of discussion, the following working definition is presented:

> *A PRP model is a computer-interpretable description of the human and machine activities and their interactions required to realize a mechanical or electro-mechanical product. This may include early concept and configuration design activities, detailed design, prototyping, testing, tooling, fabrication, assembly and the many other activities within the scope of the realization process.*

A PRP model should at least be a *procedural* model which documents precedence relationships between activities in a directed graph, and serves as a visual aid. A more robust PRP model is *parametric*, and its activity representations contain attribute/value pairs for assigned resources, duration times, cost rates, etc. By using stochastic values in a parametric PRP model, simulation techniques can help estimate uncertainty and risk for total completion time, total cost, resource utilization, and other aggregate metrics for the entire process. However, there are serious obstacles to valid parametric models given the complexity and uncertainty of real-world product realization efforts, which are discussed later in this report.

Due to multiple connotations of the term "process model" by different engineering and computer science communities, it is also useful to explain what it is *not*:

• It is not an *organization* model. A process model's scope typically crosses departmental boundaries and in fact may point to mismatches between departmental responsibility and task requirements.

• It is not an *information* model. The capability to represent temporal information such as process sequence and related time-dependencies distinguishes a process model from an information model.

• It is not just a *flowchart* of the generic sequence of design reviews and go/no-go decisions mandated within a particular corporate environment, without reference to a specific design and manufacturing effort.

• It is not a discrete event simulator for machine-executable production processes.

3. Overview of PRP Methods and Modeling Issues in Manufacturing Industries

In current practice, there are at least two conceptually distinct methodologies used for process modeling in industry which merit brief introductory comments. Readers familiar with PERT and IDEF might wish to skip sections 3.1 and 3.2.

3.1 PERT-based Models

Process modeling tools for product development efforts have been used since at least the late 1950's, when PERT (Program Evaluation and Review Technique) was developed to manage scheduling for the Polaris missile project [Malcolm 59]. As evidenced by its many commercial software implementations, PERT remains in wide use (details of PERT modeling techniques are widely available in the literature and will not be presented here). However, there are questions about the validity of PERT modeling for product development. Among product managers there seems to be a general consensus that PERT-based commercial project management software has only a very limited applicability for new product development efforts. Often, these are used only at the project outset to define very rough, graphic procedural relationships among activities. Program features such as slack time evaluation and resource allocation in PERT software are generally ignored by product development managers. Comments by [Smith 91], a manager with product development experience in electronics, are representative of design manager attitudes toward these programs:

> Many computer programs for project management are available to help with the planning effort. Although most of these programs are powerful and loaded with features, they have only one that is of much value for fast track development projects: being able to create a picture of the schedule, either in bar graph (Gantt diagram) or network (PERT or CPM) form. The best way to use these programs is to produce a giant project schedule chart and post it on the wall of the team area for all to see (a CAD system may be better than project management software for making these giant charts). Once the schedule goes up on the wall, it should stay there, in contrast with conventional uses of project management software. Normally the latter provides many kinds of reports that are to be generated on a regular basis as the schedule is updated. These kinds of reports are geared mainly to meeting government contract reporting requirements for ponderous projects and are thus inappropriate for fast development projects. [Smith 91, p. 314]

De Wit and Herroelen [De Wit 90] have documented many flaws and inconsistencies in PC-based project management packages, from erroneous completion time calculations to misleading resource monitoring and analysis. Several basic serious theoretical flaws have also been well documented, such as the PERT assumption that the total project time is approximately normally distributed [Elmaghraby 77]. Perhaps the most crucial limitation is that while PERT allows uncertainty in the *duration* of activities, it assumes the *existence* of all activities are determinant (e.g., milling machine setup and machining steps). Iteration of activities and the presence of contingency activities, which are in practice a great source of time and cost uncertainty, are neglected. Also unrealistic is the basic assumption of statistical independence of activities. These assumptions can be particularly limiting when applied to concurrent engineering activities such as design and tooling. For example, in the worst (but not uncommon) case for tooling design and fabrication, a late change in the product design can result in scrapping tools and beginning anew the tooling activities.

PERT models also have implementation difficulties in common with any activity network-based models of the product development process. Among these are i) the often informal and non-uniform determination of *which* activities to represent at *what* level of detail, ii) the difficulty of modifying a network, once built, for different product or resource configurations, iii) the selection of a probability distribution type for each activity duration time, and the subjective estimate of its parameters (e.g., the arbitrary selection of a beta distribution and best/nominal/worst case parameters used for PERT models), and iv) cost modeling limitations related to inconsistencies between the activity model and corporate financial practices. An excellent overview of the state-of-the-art for theory and practice with activity network models is found in [Elmaghraby 94].

3.2 IDEF-based Models

The Integrated Definition Methodology, commonly known as IDEF, is an extension of a representation scheme known as Functional Decomposition Diagramming (FDD). IDEF techniques emerged in the mid-1970's as part of the U.S. Navy ICAM initiative to increase manufacturing productivity [ICAM 81, Wisnosky 90]. In more recent times, many large corporations have come to develop their own "home grown" process representations and modeling procedures based on the IDEF methodology. Various extensions to IDEF tools have been developed for documenting corporate manufacturing processes at Hewlett-Packard [Marran 89], United Technologies [Davison 93], and elsewhere. IDEF has also apparently been widely used in Japan since at least 1977, despite early export restrictions on the DoD-funded documentation. A 1989 report from the Society of Manufacturing Engineers following a trip to Japan stated that many of the largest Japanese companies visited used IDEF for modeling both manufacturing and business processes [Wisnosky 94].

The original set of IDEF representation schemes, IDEF0, IDEF1, and IDEF 2, were intended as three distinct but complimentary system models from the functional/organizational, informational, and behavioral perspectives, respectively. Today, IDEF0 and IDEF1X have been formally standardized [FIPS183, FIPS184] and are being widely used in both the public and private sectors for the modeling of a range of enterprises and application domains. Common to all these IDEF types is the principle of "successive decomposition," where a simplified system diagram at a high level of abstraction points to and supports a hierarchy of increasingly detailed views of system components.

An IDEF0 model [Haines 90, Kusiak 94] is primarily a hierarchical collection of diagrams, cross-referenced with accompanying text and a glossary. The primary components of an IDEF0 model are functions and the interfaces between them. Functions are represented graphically as boxes, while the interfaces (transfers of either objects or data between functions) are denoted by interconnecting arrows. Each function box in the model represents a state transition from an input state to an output state, and is connected to the other functions of the system in specific and clearly specified ways, depending on the types of interfaces that exist. Each arrow represents a particular object or piece of information which either controls, performs, or is transformed by a function, as shown in Figure 1.

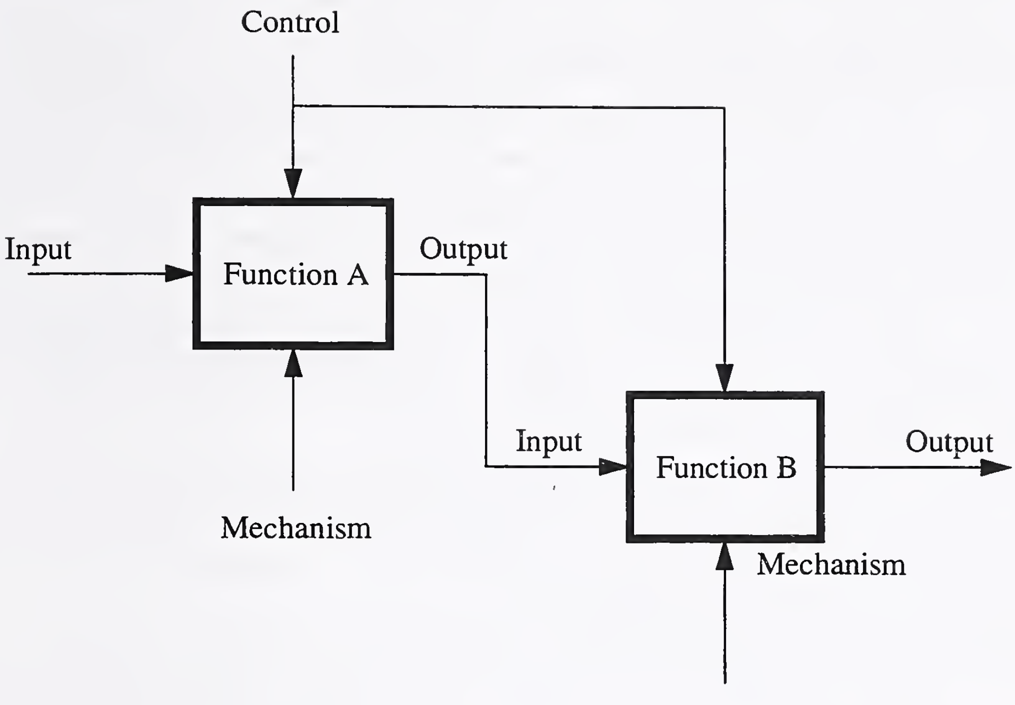

Figure 1: IDEF0 Representation

Input arrows represent any materials or information that a function will operate upon or transform during its execution, while output arrows denote the products (also in terms of material or information) that result from the function. Control arrows depict the conditions or circumstances that govern or restrict a function, while mechanism arrows represent the resources or tools (e.g., persons or machines) that are needed to support or perform the function. Together, two or more function boxes that are inter-linked by arrows constitute a constraint diagram. Within such a structure, a given function cannot commence unless its required inputs and/or controls and mechanisms (as determined by the interface arrows) are provided. The way in which the activity operates depends on the exact content of the information or objects conveyed by those arrows. Thus, IDEF0 diagrams represent only the constraints which exist for functions, and how they depend upon the outputs of other functions in a process.

An IDEF0 diagram may appear to *imply* a precedence structure between process activities, but there is no explicit representation of activity duration or process activity flow in this type of model - it is static. IDEF0 models do not convey the timing or the exact sequence in which functions *will* occur, and so they are not directly suitable for time-based evaluations (e.g., cost, time-to-market, resource leveling, etc.). Feedback and iteration can be captured in an IDEF0 model, but only in terms of functional constraints, not actual activity process flow - there is no time dimension.

IDEF1 [ICAM 81a] was developed as a methodology for producing information models that depict the relational structure and semantics of information within systems. Like IDEF0, IDEF1 is a formally structured graphical technique, but is based in relational data theory and entity-relationship modeling. IDEF1 was later enhanced to produce IDEF1X, featuring enhanced capabilities for relational data modeling. The basic constructs in an IDEF1 model are entities, attributes, and relationships. Entities, those people, places, ideas, things, etc. about which data are kept, are represented in an IDEF1 diagram as boxes. These entities generally correspond to the constraint arrows of a given system's IDEF0 model, although the mapping requires a translation of format - there is no direct, natural correspondence between constraints and attributes. Consequently, a set of linked glossaries is required to couple and allow translation between the IDEF0 and IDEF1 representations of a system. Attributes in an IDEF1X model are descriptive characteristics belonging to entities, and each entity has its own particular set of attributes, shown as text located within the graphic entity boxes. Associative relationships and connectivities between the informational entities are represented as lines that inter-connect the boxes in the diagram. In short, the informational IDEF1 representation for a system shows how the arrow labels (constraints) in the functional IDEF0 representation of that system are related.

IDEF2 was developed as a means of producing "dynamic models" intended to represent the time-varying behavior of systems in terms of the functional, resource, and informational characteristics depicted by IDEF0 and IDEF1. However, IDEF2 is not in wide use today, and has largely been superseded by commercial approaches [Wisnosky 94].

It should also be noted that these IDEF methodologies were initially developed to model very large scale design and production for aerospace and other defense-related systems. Attempts to use IDEF for modeling in other domains such as small batch, flexible manufacturing systems (e.g., apparel manufacturing) have revealed some limitations [Malhotra 92].

3.3 Traditional PRP Modeling Practices

When one looks beyond the "best practices" in the more advanced manufacturing corporations, documentation on most PRP's is created with little standardized format, at a very crude level of detail and without consistency of activity definitions. Consider an application of a Gantt diagram from one 500-person "mature" manufacturer of metal assemblies forced to redesign its products due to competitive market pressures. The Gantt diagram in Figure 2 was produced by the product development team (proprietary references have been omitted). Each activity implicitly refers to the entire product assembly, and the resulting high level of abstraction makes this a document of very limited use. "Activities" here include milestones in the project, beginning and ending of major project phases (e.g., "preliminary design"), and specific tasks performed by marketing, manufacturing engineering, product engineering, and tooling engineering. The "duration time" arrow indicators group large numbers of these activities together in the same time period, and do not portray dependency or precedence relationships between individual activities. In this instance, these Gantt diagrams were distributed to department managers at project inception, and then more or less ignored when later design iterations, change in management priorities, and delays in production ramp up occurred.

ACTIVITY	WHO	STATUS	JAN	FEB	MAR	APR	MAY
1. start formulation	MKT		M				
2. market specification	MKT		->				
3. end formulation							
4. start preliminary design	PE,ME,TE	R	M				
5. CAD input (shaded images)	PE	R	------------>				
6. stereolithography	PE	R	------------>				
7. design/function spec comp	PE	R	------------>				
8. issue matl specs	PE	R	------------>				
9. initial product review	PE	R	------------>				
10. prelim cost parts & matl	ME		------------>				
11. prelim process cost	ME		------------>				
12. prelim eng analysis doc	PE	R	------------>				
13. prelim parts list doc	PE	R	------------>				
14. prelim drwgs/dims	PE	R	------------>				
15. rough design documented	PE	R	------------>				
16. gage/fixture/tool concepts	ME			------------>			
17. issue critical tolerances	TE			------------>			
18. long lead items complete	ME			------------>			
19. prelim capacity analysis	ME			------------>			
20. risk mngt plan issued	ME			------------>			
21. standard cost issued	ME			------------>			
22. tol stud (mjr comp) signed	TE			------------>			
23. inspect & test proc issued	QA			------------>			
24. engineering product review	PE				---------------->		
25. prelim dwgs -all parts issued	PE				---------------->		
26. final parts list issued	PE				---------------->		
27. potential prob analysis/risk	TE				---------------->		
28. end preliminary design							M

Abbreviations:

MKT = Marketing Dept., PE = Product Engineering Dept., TE = Tooling Engineering Dept.

R = resource conflict, M = milestone, "--->" = activity duration

Figure 2: Gantt Diagram application at a mid-sized, "mature" manufacturer

3.4 Emerging PRP Model Applications in Industry

Beyond their traditional role as a high-level "road map" for project management, PRP models are being called upon for a range of applications. For example, many companies have been strongly motivated to significantly refine their PRP models when they decide to initiate a system-level integration of CAD software. Obviously, the introduction of integrated CAD systems can alter existing processes and, ideally, eliminate certain tasks such as physical prototyping for evaluating assembly fits. Constructing "as is" and "to be" models provides a basis for justifying organizational change. A related application has been to document and revise the engineering change order (ECO) process. Watts [Watts 84] describes the use of such models to aid process decision-making and deployment resulting in ECO lead time reduction. Process modeling tools are also being called on to examine requirements for supplier chain information flow in distributed product development. For example, PRP models are being used as part of a project to examine integration requirements for supplier chains for automotive and military applications [ITI 94]. Both interorganizational and internal information flow of the "as is" system is being modeled as a precursor to developing common semantics for the entire procurement process. Most recently, industry use of PRP models has been promoted under the guise of "Business Process Re-engineering" (BPR).

3.5 Industry Requirements for PRP Models

What are the decision-making needs of engineers and managers which should drive development of advanced PRP modeling tools? These tools should help evaluate the downstream implications of complex design process interactions that span traditional engineering departmental responsibilities. Some possible scenarios for which advanced PRP tools might be useful include:

Best Practices: For most industries it is critical to understand successful business practices to provide a guideline for future projects and product development efforts. Equally as important is the documentation of "lessons learned' to prevent problems from being encountered and solved again and again. Many industries develop these guidelines for different processes, yet usually this information is static and maintained in paper form. Updates to these guidelines are rarely timely and maintenance becomes a significant barrier to acceptance. Development of electronic models can enable more timely updates and version control by spreading the maintenance across more people.

Cost Estimation: For large complex projects it is very difficult for contractors to predict the effort required to meet the projects objectives. It is also difficult for the project sponsor to determine if the contractors' proposed expenses are reasonable to meet the defined objectives. The development of a general format PRP model template which could be tailored could increase a company's confidence in cost estimations. In addition, the PRP model will assist in identifying key cost drivers which might reduce costs further by early discussions with the sponsor on cost reduction.

Insertion of rapid prototypes: With the evolution of rapid prototyping technologies, product realization cycles can be shortened with the inclusion of rapid prototypes in the PRP. By including new prototyping subprocesses in a "to be" PRP model one can better predict their impact on the product realization cycle and from this a more informed decision on process improvement can be made.

Selection of materials: Specification of different materials for product components can result in significant product improvements (i.e., cost reductions, increased reliability) yet associated with this decision are downstream uncertainty for fabrication, on-site and field testing. Depending on the functionality of the component, the material selection might affect several organizations and these considerations need to be planned for and addressed. To do this requires one to understand all the dependencies associated with the material selection. Often, the material property information is very limited which increases the uncertainty and risk of a specific material (for example, some polycarbonates only have strength data derived from simple tensile testing). Increased risk also results if product functionality uses the material in a novel way (high impact stresses, intensive thermal cycling).

Evaluating new manufacturing processes: Introduction of different or innovative manufacturing processes (e.g., metal injection molding for previously machined parts, stereo-lithography) can be a source of uncertainty for downstream activities. Designers and manufacturing engineers may be unfamiliar with practical process limits and their effect on part conformance to tolerance requirements. In addition it is often difficult for manufacturing engineers to define new ramp-up activities and estimate activity durations for implementing new processes. Manufacturing engineers may, in some cases, strongly resist process innovation and provide unrealistically negative estimates of time and cost impacts. Conversely, managers and product engineers may push for the new process with unrealistic expectations. Representation of these uncertainties in PRP models can assist in making engineering decisions regarding the benefits of the new process.

Selecting a fabrication method for prototype builds: Complexities arise when managers examine the consequences of prototype fabrication decisions for later downstream activities. Are the prototypes built with the same manufacturing processes as will be used in production (for example, wire EDM of prototype parts when progressive dies are to be used in production)? If a different process, then downstream delays may occur when the production tooling and set-up issues are addressed. Also, dimensional and structural properties of prototype components may differ in ways that seem insignificant in preliminary testing, but later become problems (e.g., stress concentrations that occur in forming but not metal cutting).

Number of preproduction units: Even when the same manufacturing process is used, how many production prototype models should be built? Prior to final design sign-off and production tooling, manufacturing engineers prefer longer test runs, while management is anxious to enforce "concurrency" by minimizing the time required for this stage of development. If only 5 or 10 parts are made, then the machinists and other direct labor involved in their fabrication will treat these as "specials," and many of the problems that occur in actual line production may not surface. (For series of machining operations on parts, a rule of thumb at one company is that about 100 parts are needed to validate producibility.)

Traditional 2-D vs. 3-D parametric modeling: Design engineers and computer-trained draftsman increasingly advocate the use of 3-D, parametric CAD systems. However, serious downstream delays may occur when 3-D modeling is introduced in companies that do not restructure their downstream activities to make use of these systems. Many machinists, cost estimators, tool designers, etc. still only know how to analyze 2-D graphical data. If 2-D drawings have to be generated from a solid model representation, the work required for layout drafting, revisions, fixture design, etc. can actually *increase*. (Interestingly, one of the most important features in parametric modeling systems -- which many promise but cannot fully deliver -- is easy generation of traditional 2-D drawings from 3-D data.) With PRP models managers have a method to consider the impact of advanced CAD systems which can expedite early design and analysis, but actually impede downstream activities that still rely on traditional blueprints.

Project prioritization: In many companies, a list periodically circulates that prioritizes different product efforts. For many of the Product Engineering support operations such as drafting and engineering change requests, new product projects directly "compete" for priority with on-going minor product variant efforts. This priority listing may change weekly in response to management perception of delivery commitments. Managers have difficulty viewing the long-term effect of this prioritization on new product lead-time and overall company objectives.

Alternate subassembly configurations: Two alternate subassemblies may both meet functional requirements and spatial constraints, but differ in use of physical principles and/or manufacturing processes. For example, a sheet metal retaining clamp in a battery-operated beard trimmer has an alternative double-coil spring which serves the same function. If the spring is purchased but the clamp is tooled and fabricated in-house, some aggregate measure of their alternate effects on downstream prototype assembly, pilot runs, etc. is desired.

Budget requests: Both manufacturing and product engineering managers are under pressure to submit low-cost budget requests for development activities. Because they are necessarily "uncertain" what the actual downstream expenses will be, they are forced to choose between i) padding known line items in the request with hope that this surplus will cover contingencies and possible design "iteration," or ii) submitting a lower-cost budget, then face the unattractive consequence of petitioning for more money under the perception that they are "over budget."

Schedule assignment: Typically, groups in manufacturing, design, etc. submit their desired schedules to upper management, upper management then compresses the requested time for each activity, and distributes a "master" schedule for the project. For managers, there is no way to explicitly examine the trade-offs, for example between greater time allotted for preliminary design (e.g., more thorough testing of early models, or more early effort on manufacturing tolerances), and more time for downstream manufacturing ramp up.

Capital expense for design: Capital expense for new equipment in a design engineering group is often difficult to justify compared with manufacturing capital requests. A new CNC machine can be easily justified in cost savings to production, but paying $250,000 for a stereolithography system has potentially greater, though much less certain, payback. Development cost "savings" are difficult to discern since accounting is primarily focussed on unit production costs.

Engineering change order requests: Invariably, requests for design changes after the design is supposedly "fixed" are made by marketing, product engineering, and manufacturing. Weighing the potential cost and lead time effect of each change can be difficult. This is particularly true since each department typically signs off on the proposed change "in series:" the paperwork travels from one desk to another, often with considerable delays between departments.

4. Modeling Issues for Advanced PRP Computer Tools

We begin with some caveats about the subjectivity inherent in product realization processes that distinguishes them from strictly machine-executable processes. The modeling implications of this subjectivity might be grouped into two areas: 1) the *structure* of the model (e.g., defining activities and their precedence relationships in a directed graph), and 2) the *content* of the model (e.g., *values* of activity attributes which allow parametric characterization of activity duration, branching probabilities, and quantitative evaluation of time, cost, etc.). Because they model sequences of human-executable as well as machine executable activities, the structure of a PRP model is inherently subjective in its capture of information flow. It would be a mistake to consider any such activity representation as a formal *function* representation which has repeatable, one-to-one or many-to-one relationships between inputs and outputs. The nature of organizational behavior makes a rigorous mathematical definition of its semantics unlikely. Unlike the clear sequence of fabrication activities in physical process planning, PRP models must often characterize a very ambiguous information flow. The natural tendency for those constructing the model is to define activities in terms of tangible inputs and outputs such as written specifications, analysis results, and material transformations. However, much information flow in a PRP is less easily specified, such as the informal communication network built up in an interdepartmental concurrent engineering team. Documenting these transactions is somewhat analogous to problems with the "knowledge acquisition" process acknowledged for expert systems development.

Beyond simply documenting activity precedence, how effectively can PRP models provide aggregate, quantitative metrics such as total cost and project completion time? This raises issues about the subjectivity of *content* in a process model such as estimation of activity duration time and assignment of branching probability values (for example, the pitfalls of assuming beta distributions for modeling time uncertainty in probabilistic PERT models).

With these caveats in mind, some of the many representation issues for advanced PRP modeling will be discussed.

4.1 Activity Network Representations

There is an extensive literature in activity network representation and related graph theory, but we need only introduce some nomenclature to help frame the discussion that follows. Many *parametric* process representations which extend the standard PERT representation (e.g., to include stochastic branching) have been developed for general use since the mid-1960's. Most advanced network models are built upon antecedents such as Graphical Evaluation and Review Technique (GERT) [Pritsker 66]. Both activity-on-node and activity-on-arc representations are used in network modeling practice. Visually, an activity-on-arc representation might have some advantage since it could potentially display time scales in terms of arc length. Consider, for example, how a Generalized Activity Network (GAN) representation as defined by [Elmaghraby 77] might be adapted for PRP modeling. For the primary building block in the network, an activity (see Figure 3) is represented as a transition (arc A_i) between initial and final states (nodes a, b):

$$A_i = (p_i, t_i, c_i)$$

Figure 3: Generalized Activity Network (GAN)

The parameters for the vector A_i are:

p_i: probability that the activity occurs given that node *a* is realized

t_i,: the duration of the activity (a random variable)

c_i: the cost of the activity (a function of t_i and other resource usage)

In the standard nomenclature for GANs, an activity has *receiver* and *emitter* logical conditions associated with its initial and final states which are graphically displayed in two halves of the nodes such as those shown in the Figure 4 below.

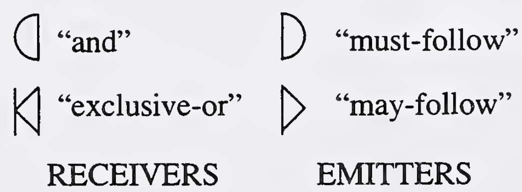

Figure 4: Node conditions for a GAN

A logical "and" receiver initiates the immediate follower activities when all immediate preceding activities have been completed. A logical "exclusive-or" receiver initiates the follower activity when one, and only one, preceding activity has been completed. A "must-follow" emitter denotes deterministic realization of a follower activity, and a "may-follow" emitter denotes probabilistic realization. In principal, there exists an analytic approach for solving a GAN by transforming the network to one which contains only "exclusive-or" emitters. Under the assumptions of a semi-Markov process, this network then will have an analogous representation as a signal flow graph, and analytic solution. However, an *analytic* evaluation of cost and time distributions for activity networks of the complexity required for PRP models would be unwieldy; either some PERT-type simplifying assumptions or a simulation approach must be considered. While simulation models have been used extensively and successfully for modeling manufacturing processes (e.g., queuing models for assembly lines), they have apparently been rarely used to model product realization processes.

4.2 Representing Design Iteration and Activity "Overlapping"

There are certain types of activity iterations, unique to discrete product realization, which should drive advanced PRP modeling efforts. A much-cited field study by Clark and Fujimoto provides empirical evidence that the dependency between product and process design activities is an important factor for determining development lead time [Clark 89]. In a comparison of auto body design and die fabrication activities in Japan and the U.S., they suggest that "overlapping" of these activities can shorten development time if information processing and production resources are adequate. Two types of management factors are identified that facilitate effective overlapping: i) the structuring of effective communication between engineering groups to allow downstream decisions based on incomplete design data, and ii) choosing the earliest time to commence the downstream activity (e.g., cutting a contoured die) such that premature commitments are minimized, and costly iteration of die design and fabrication activities is avoided. Ideally, any model of the development process to aid decision-making should represent both types of factors. For (i), a model might aid decision-making by relating uncertainty in product information to uncertainty in total development cost and time. For (ii), a model might examine alternative times for commencing "overlapped" activities, and relate each to total cost and time.

"Design iteration" is a loosely defined term which describes the cycling of subgroups of activities typical in most PRP processes. For example, one particularly costly problem with design iteration in industry is design and tooling activity "iteration." There are many anecdotal examples of this conveyed to the authors, including: i) a "counter" device in the production prototype of a high-volume camera which, after review by upper management, had to undergo redesign and tooling rework; ii) a new model photocopier in pilot production which was discovered by marketing personnel to have too large of a "footprint" for its intended Japanese market; iii) an innovative small firearm already in pilot production which required considerable redesign and retooling due to inadequate specification by an ammunition supplier. Another example of "iteration" in the design cycle for downstream tooling activities was relayed to this researcher by engineers at a large manufacturer of heat pumps. A product line consisted of a compressor, heat exchangers, and an accumulator (i.e., thermal capacitor) placed in close configuration on a base plate stamped from cold rolled steel. The positions for these heat pump subassemblies determine the various depressions and punched holes in the base plate required for drainage, from which a base plate design is determined and sent to a progressive die vendor. The resulting die tooling is complex, and typically costs $1/2 to $3/4 million. However, after the base plate tooling had begun, changes to the "footprint" of the compressor and other subassemblies would occur as technical advances required their redesign. This in turn required that the entire base plate tooling be scrapped and started over to accommodate a new configuration of the subassemblies.

Two types of activity interrelationships that defy analytical solution for the resulting network model are: i) redesign iteration which occurs during proof-of-concept, production prototyping, and other phases of engineering design, and ii) changes to or cancellation of manufacturing process activities concurrent with product design when the redesign iteration in (i) occurs. For the first type, design is often informally described as an "iterative" process, and in fact many sequences of activities in the early design phases are repeated. The use of iterative looping in an activity network is an imperfect but potentially useful representation of the uncertainty associated with activity "overlapping" as described by [Clark 89] and identified by many companies as "concurrent" or "simultaneous" engineering of product and process. In the best of circumstances, overlapping product and process activities can significantly shorten development cycles, but a high level of communication is required between design and manufacturing engineers. For example, a die designer might be able to discuss in-progress styling or structural features proposed by a product designer and construct a die with metal unremoved in die regions where he anticipates possible changes. In practice, the risk in this approach is very dependent on the interpersonal relationships among engineering group members.

In terms of the representational requirements for concurrent activity interdependencies described above, it is instructive to examine the simplified network for design and tooling shown below in Figure 5.

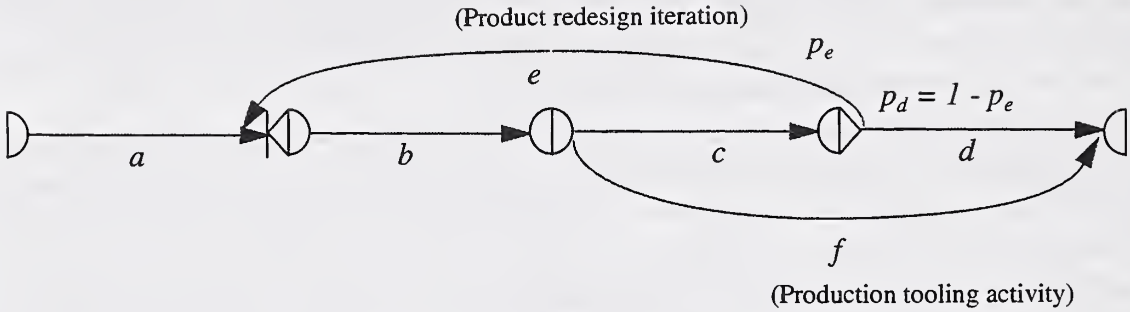

Figure 5: Activity interdependency in a GAN

As a way to simulate the concurrent design situation described above using this model, the production tooling activity *f* must terminate at the same point in system time when the iteration activity *e* is realized (i.e., the duration for *f* is not statistically independent). When activities *b*, *c* and *f* then occur for the second time, the parameters for the distribution functions of the random variables t_b, t_c and t_f, have changed. Similarly, the branching probability p_e should also change after successive redesign loops.

4.3 Uncertainty Modeling of a PRP

4.3.1 Some Simulation Considerations

In exploring a simulation approach, it should first be noted how the type of simulation required for the product realization process differs from manufacturing process simulations. Manufacturing simulations are typically based on queueing models. The objective is typically to simulate steady-state workflow conditions in a sequence of production operations where successive units come "down the line." By analyzing the simulation results, bottlenecks in processing, buffer size requirements, capacity, cycle time, and other parameters can be identified and optimized by changing the configuration of processing tasks and resources for people, equipment, and materials.

By contrast, the type of simulation required for a product realization process analyzes a single "unit" -- the design itself -- as it increases in complexity of informational and physical detail by undergoing tasks within the various company departments. In the nomenclature of simulation, a PRP model is a "terminating system." That is, there is a point in time at which an "epoch" is completed and all discrete events cease. This is in contrast to a non-terminating system, for which discrete events continue indefinitely, and the simulation is stopped at some arbitrary point in time. Unlike in a manufacturing process, the description of the "unit" itself is not predefined, and is actually being transformed during its development. Because of this, there is uncertainty inherent in task duration and iteration that is not present in a manufacturing simulation. Time variability in manufacturing simulations is typically aggregated from delay times in queues and by machine down-times on a production line (that is, by waiting times between the fixed task times in a production sequence). However, in a PRP simulation, virtually all task times must have variability and iterative loops must be characterized. Also, due to the abstract nature of product realization, the network configuration and parameterization of activities is more subjective; any output from a PRP simulation is subsequently less precise.

4.3.2 Activity Duration Uncertainty

Analysis of the total time and cost uncertainty for a product realization process is dependent on characterization of uncertainty in individual activity durations. In common practice, probability distributions assigned for product development activities are often quite arbitrary (e.g., the beta distribution assumption in the commonly accepted PERT network model) and are based on analogous activity distributions evidenced in physical manufacturing processes. Activity times in a PRP model might fall into two general classes: *lead times* and *work times*. Lead times (e.g., delay times for many "over-the-wall" hand-offs of design information within an organization) might be represented by exponential distributions. Processes modeled by the exponential distribution include queues (for banks, grocery check outs, etc.), time between failures in electronic devices, duration times of telephone conversation, and, in general, many processes modelled using the theory of congestion systems. Work time distributions (time to create a detailed design, prototype, etc., as well as order time for purchased components, subassemblies, or materials) are perhaps best represented by a two-tailed distribution skewed to the right which might be modeled by beta (used in PERT), gamma or other distributions. Many studies of "work" activities have shown them to be gamma distributed, such as many manual tasks in assembly operations [Hoover 89]. One convenient property of using exponential and gamma reference distributions is the ease with which distribution parameters can be estimated from sample means and standard deviations. (This contrasts with parameter estimation for the beta distribution, for which multiple parameter values are possible given estimates of mean and variance, and which leads to problems under the simplifying assumptions of the PERT model.)

Computational costs are another consideration. For a practical PRP model with upwards of 100 activities and using Monte Carlo simulation, random variate generation will contribute considerably to CPU time. Computation is relatively simple for the exponential distribution, and a simple inversion method is adequate for random variate generation. However, for the gamma distribution, and in general for most two-tailed asymmetric distributions, random variate generation is somewhat more involved. For example, random variates for the gamma distribution

$$f(\alpha, \beta) = \frac{t_w^{\alpha - 1} e^{-\frac{t_w}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \qquad \text{[Eq. 1]}$$

are most simply generated for the case of $\beta = 1$ (the standard gamma distribution). Different algorithms are required for the cases of $\alpha > 1$ and $\alpha < 1$ ($\alpha = 1$ is simply the exponential distribution). Of the possible algorithms described by [Dagpunar 88], all are iterative in that a rejection test is required for the generator. For $\alpha > 1$ an approach can be used based on the ratio of two uniformly distributed random variables. Intensive simulation of large-scale PRP networks with hundreds of activities is quite computationally expensive.

Yet another duration uncertainty issue is the changing status of cost and time estimates as the project progresses. A Bayesian methodology has been suggested to update distributions as actual cost/time data is fed back into the system during project execution [Huseby 93].

4.3.3 Concurrent Activities and Stochastic Modeling

As discussed regarding the limitations of PERT models, the mean and variance for the aggregate time of the network may differ substantially from the sums of the expectations for individual activities along a deterministic "critical path." In general, the greater the number of parallel arcs in the network the greater the discrepancy between total time as predicted from a PERT model and the actual expectation of the network time. For many traditional applications of a PERT model, in which there are relatively few parallel paths and a single, dominant "critical path" exists (e.g., construction projects), this discrepancy may not present a problem. For product realization processes, however, this discrepancy could be quite large. Consider an example assuming multiple parallel paths (Figure 6) where the completion time of each is an identical random variable T_i (analogous to the problem in reliability theory for the prediction of failure rate for components in parallel.) For simplicity, assume that the paths are identically distributed with the uniform distribution *U(0,b).*

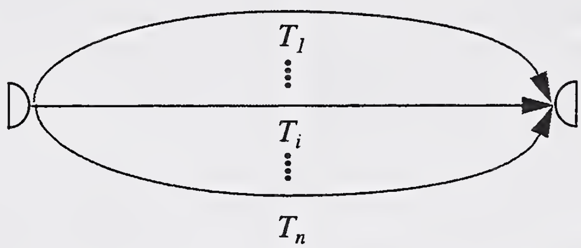

Figure 6: Parallel paths (concurrent activities) in activity network

The total completion time $X = Max\ (T_1, T, ..., T_n)$, and for the cumulative distribution function,

$$F_X(x) = F_{T_1}(x) \cdot F_{T_2}(x) \ldots \cdot F_{T_n}(x) \qquad \text{[Eq. 2]}$$

$$= \quad [F_{T_1}(x)]^n = \left(\frac{x}{b}\right)^n \qquad \text{[Eq. 3]}$$

if independence for the uniformly distributed completion time of each path is assumed. For the p.d.f.,

$$f(x) = \frac{\partial}{\partial x}[F_{T_1}(x)]^n = \frac{nx^{n-1}}{b^n} \qquad \text{[Eq. 4]}$$

for which the expectation is

$$EX = \int_0^b x f(x) dx = \frac{nb}{n+1} \quad \text{[Eq. 5]}$$

and the variance is

$$VarX = E(X^2) - EX^2 \quad \text{[Eq. 6]}$$

$$= \int_0^b x^2 \left[n \left(\frac{x}{b} \right)^{n-1} \right] dx - \left(\frac{nb}{n+1} \right)^2 = \frac{nb^2}{(n+1)^2 (n+2)} \quad \text{[Eq. 7]}$$

For each uniformly distributed individual path, $ET_i = \frac{b}{2}$ and $VarT_i = \frac{b^2}{12}$. As would be intuitively expected, the mean of the total completion time will always be larger than the mean time of any single path.

Estimating total completion time uncertainty in an activity network is also related to the level of detail of the activities being characterized. The time-to-completion variance of a single, high-level "activity" will be greater than the summed variances of subdivided, lower-level activities if one assumes (as is done for PERT models) that i) the total expected time of the subdivided activities at the lower level of detail is equal to the expected time of the single, aggregate activity, and ii) the range of the subdivided activities equals the range of the aggregate activity. In addition, analysis of time and cost variability for complex networks is complicated by subjective estimates of distribution parameters:

> There is little doubt that the estimates of the parameters of individual activities combine in a complex manner to yield the estimate of the variance of the project duration. Errors in such parameters introduce errors in the final result, whose magnitude and direction remain, to date, largely undetermined. [Elmaghraby 77, p. 258]

4.3.4 Alternative Representations of Uncertainty

Although a probabilistic concept of uncertainty is used for activity duration in most models, there are other mathematical tools available to characterize time variables, and provide for binary operations on those variables. One possible method might be a relatively simple application of Zadeh's extension principle for fuzzy numbers [Wood 89]. As an example, a variable such as activity work time for a particular life-cycle stage would be denoted not by a discrete value but by i) an interval of confidence [l, u]; and ii) a membership function which assigns a membership $\alpha \in [0,1]$ to define the level of confidence for values within the interval (0 is least confident and 1 is most confident). For example, work time durations for prototyping P and testing T might be denoted

$P = [p_l, p_r] = [10, 20]$ days and $T = [t_l, t_u] = [15, 30]$ days with corresponding membership functions shown in Figure 7 below.

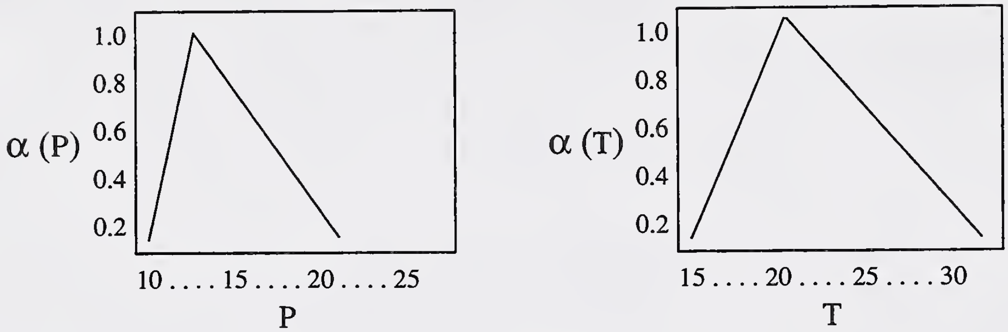

Figure 7: Examples of fuzzy membership functions

The completion time for both prototype and testing, at a given level of confidence, would be

$$C_\alpha = P_\alpha \oplus T_\alpha = [p_l^\alpha, p_u^\alpha] + [t_l^\alpha, t_u^\alpha] \qquad \text{[Eq. 8]}$$

$$= [(2\alpha + 10) + (5\alpha + 15), (-8\alpha + 20) + (-10\alpha + 30)] \qquad \text{[Eq. 9]}$$

where $\oplus$ is the fuzzy addition operator. For confidence intervals for C_α at alpha levels 0, 0.5, and 1.0,

$C_0 = [25, 50]$
$C_{0.5} = [28.5, 41]$
$C_1 = [32, 32]$

This type of uncertainty characterization has not been widely used for activity network modeling, however, and network analysis difficulties are likely. It is mentioned here only as a possible alternative to the probabilistic characterization.

4.4 Representing Economic Information

Ideally, a PRP modeling tool would help evaluate the strategic economic impact of candidate product and process design configurations. Design trade-offs could be examined for their impact on both costs and revenues, and related uncertainty, during the entire product life-cycle. We will first discuss some cost modeling issues and then examine the potential for more "strategic" economic analysis within a PRP model.

One obvious cost analysis problem for PRP models is determining the differential impact of product and process changes using data tied to traditional overhead allocations in industry accounting practices. For example, for many traditional manufacturers, new product design is relatively infrequent, and competes for scarce engineering resources with on-going manufacturing and minor design variations to existing product lines. Their cost accounting practices often assign overhead costs for their product development efforts using an accounting "base" formulated for on-going production. New activity-based costing (ABC) methods seem to be relevant, and have begun to be incorporated in commercial IDEF-based process modeling tools for “Business Process Re-engineering.” Other relevant work on activity-based cost modeling includes work by Bloch [Bloch 92] and Reimann [Reimann 94].

Time-dependent costs are another issue. One approach might be to modify traditional cost models to enhance PRP model sensitivity to the time-to-market implications of design decisions. For example, Ulrich [Ulrich 91] suggested the following cost model after studying Polaroid’s product development efforts:

$$C = V(m + l + p) + F + S + D + T \qquad \text{[Eq. 10]}$$

C: total manufacturing cost of the product over its lifetime
V: total production volume over the product lifetime
m: unit material cost
l: unit direct labor cost
p: unit production resource usage cost (e.g., machine time cost)
F: product specific capital costs (e.g., tooling, jigs, and fixtures)
S: system costs
D: development costs
T: time costs

In this model, the terms *V* and *F* on the right hand side contain the traditional costing terms described previously. *M*, *l*, and *p* correspond are the unit material and variable costs, and *F* corresponds to the fixed costs. The terms *S, D*, and *T* are traditionally not considered in product cost evaluations. *S* refers to those institutional system costs that are normally aggregated as overhead costs for direct production cost rates. These include industrial engineering, plant maintenance operations, material control, purchasing, and other functions. *D* refers to development costs: direct labor for engineering staffs involved in product and process design, product modeling costs, and other non-recurring expenses prior to on-going production. *T* is a cost associated with the total product development lead time. This time-related cost is generally not explicitly considered in a financial evaluation of the product. It may include revenue loss due to late market entry, a shift in present worth or internal rate of return (IRR) for capital expenses, or an opportunity loss cost due to delayed technology introduction following along time-to-market.

Ulrich posits that for certain product types for which short lead time is critical for competitiveness, this cost *T* is important or even predominant, and new product cost models are required to evaluate its magnitude and dependency on changes of product attributes. This time criticality, he states, makes some of the established design-for-manufacturing heuristics inadequate for these product types. In a field study, his research group examined a late production model of a Polaroid camera - a large volume consumer product for which short lead time is critical to sales of both the camera model and its self-developing film. Engineering designers had followed an accepted DFM convention: reduce the number of parts to simplify assembly operations, even when the resulting parts require increased complexity (e.g., replacement of screws by snap fits). As a result, one single injection-molded part in the camera frame required an exceedingly complex design to accommodate part reduction, ease of assembly, and multiple functionality. The lead time for its injection mold tooling was considerably longer than any other part, and therefore determined the critical activity path for the entire camera development effort. Development costs as defined by this model are considered to be difficult to assess because

> the relationship between part details and engineering effort is considerably more complex than the other relationships we have modeled. [Ulrich 91, p. 13]

Development costs were assumed to be "roughly independent of the design details," and were neglected in the Ulrich model. However, in many companies, the proportion of operating costs related to engineering development of new products is growing substantially, but the cost measurements of these development activities continue to be tied to activities within the same departments and work units that support on-going manufacturing. In some cases, seemingly routine design detail decisions, particularly those which have some element of risk related to innovative product function or manufacturing process, can affect development costs substantially.

Many multinational manufacturing firms use computerized business simulations to train executives and explore alternate scenarios for "strategic" business decisions (for example, these have a long history in the auto industry [Bonini 63]). Their economic modeling concepts might have application for PRP modeling tools. However, their cost modeling methods appear to still be based on simple variations of the traditional *production function* concept in economic theory. The standard Cobb-Douglass production function, for example, assumes only crudely defined inputs of labor and materials. Gold [Gold 92] and others are experimenting with production function refinements for manufacturing business simulations. Son [Son 92] has also developed a manufacturing cost simulation methodology using advanced cost accounting principles.

Modeling the downstream *revenue* impact of design decisions has begun to attract interest in the design engineering community. Devor and Cook [Cook 91], both prominent mechanical engineering academics, have attempted to frame the "demand side" of design evaluation within a larger "strategic" economic model. In actual practice, though, modeling tools that incorporate revenue are limited to simple spreadsheets. [Smith 90] has described this traditional cash flow approach: for a "baseline" development scenario, annual revenue is projected during market life from selling price and expected unit sales, and development, production, marketing, and distribution costs are assigned. Variations to this baseline scenario can then be examined, such as delayed time-to-market, product cost, product performance, and development expense. Smith argues that since only very approximate data is available at the early design stage, such models must be very simple. For example, to examine trade-offs, he encourages use of rough rules-of -thumb such as "$100,000 of additional development expense per 1% increase in performance" [Smith 90]. It is unclear to what extent more systematic, detailed methods of cost and revenue estimation might improve this type of cash flow approach within a computer-based PRP modeling tool. Fairly accurate estimation of a revenue curve has historically been possible only for certain product types. In particular, companies which can elicit marketing feedback from well-organized distribution and service channels and have a fairly stable competitive environment (some examples are air conditioners and furnaces) have historically made fairly accurate predictions in the five-year range for unit sales of new products. In general, though, and particularly in a new era of more dynamic international markets, this type of revenue prediction is extremely difficult. However revenue flow can sometimes at least be parameterized using a scheme such as that described by Haffner [Haffner 88].

4.5 Data Collection and Validation Issues for PRP Models

Obviously, the collection of valid data to populate a PRP model is critical [Busby 93]. For reasons already cited, these data will certainly be less precise than for a machine-executable production process. Defining discrete activities - let alone iteration loops - is sometimes arbitrary. For example, tolerancing on part drawings may be done partially by a design engineer, partly by a draftsperson, and partly by manufacturing personnel at different stages prior to fabrication. For assigning activity durations, there are a variety of established techniques for subjective estimation of probability distributions in network models. These include the Normalized Geometric Vector method, the Modified Churchman-Ackoff Method, and the Delphi Technique (an overview of the use of these and other methods for cost/time data uncertainty can be found in work by Stewart [Stewart 87]). For less formal parameter assignments for activity times, either historical data from similar projects or subjective estimates can be used to obtain mean and standard deviation values. The relationships between resource allocations and activity durations is also problematic. (In fact, some would argue that an inverse relationship exists in some cases. In Japan, which has the shortest design cycles for most discrete product groups, the number of core design engineers for many electro-mechanical products is typically less than 30, while design staffing for similar products in the U.S. may be in the hundreds. [Whitney 90]).

More generally, some difficulties for parametric PRP modeling should be made clear. [Wall 91] has discussed time and cost estimation for a field study of prototyping activities at the Kodak Apparatus Division:

> A number of factors make estimating processing time and cost difficult. First, the reliability and consistency of the estimator has to be established. In many organizations estimating is still more art than science; often the estimators would produce one estimate then start over as they realized a more elegant solution to the fabrication problem. Second, we had to define where one process finished and another started, and we had to define the "average" target level of performance for each process. For example, a stereolithography part destined for the paper path of a copier required more hand finishing time than a similar stereolithography part designed to hold rolls of film. Third, the skill levels of the operators were also an issue. Fourth, we often found variations within a given process; a given part can often be fabricated by a given process a number of different ways. Finally, the capacity utilization level of the process determines the time a part will spend waiting for the process. For the time estimates, we assumed that capacity utilization was low enough that the queueing effects were negligible. This will only be true in organizations that allocate enough capacity to prototyping that jobs move through the shop without contending for resources. [Wall 91, p. 153]

This last assumption by Wall (negligible waiting time to begin an activity) was quite reasonable within the context of his study, but is probably unrealistic for modeling time-to-market determination within the context of most companies.

There are considerable difficulties to industry-relevant validation of experimental PRP models. This holds for their process visualization capabilities as well as parametric properties for predicting aggregate cost and time estimates, etc. Validating an aggregate development cost and time model with "real" industry cost and time data is difficult for three reasons: i) only a subset of design and manufacturing activities is typically modeled, ii) current accounting practices at most companies cannot provide meaningful comparison to activity-based costing, iii) "to be" models are essentially un-calibrated in terms of distribution parameters for activity durations, branching probabilities, and conditions for dynamically changing state variables in the network. Ulrich [Ulrich 91] has discussed similar validation problems for aggregate development time-dependent cost models in the course of field research at Polaroid:

> Even defining accuracy within the context of a cost model of this type is difficult. The problem is that actual costs are incurred at a very aggregated level over some period in the past and we would like to estimate what future costs will be under a different set of conditions. The manufacturing system is much too large and expensive to run model validation experiments. The best one could do is to compare predictions with outcome for the one particular set of design choices that happen to emerge in the next product cycle. Instead, we carefully examine the underlying assumptions of our model and attempt to justify each of its constitutive elements. If we believe the assumptions, we should believe the implications of the arithmetic linking the assumptions to cost. The power of models like these is that they facilitate exploratory calculations. Researchers and program managers can test the impact of different detail design strategies under different sets of assumptions to gain insight into how detail designs impact manufacturing system performance. [Ulrich 91, p.7]

4.6 Knowledge-Based Representations in PRP Models

Though some PRP modeling packages have claimed to be "knowledge-based," their use of this term refers mostly to generic graphical and data-linking enhancements. We have discovered no existing models which can embed domain-relevant "knowledge" about activities and their interactions that significantly enhances either model construction or analysis. However, there are several ways that one might envision using knowledge-based design paradigms for PRP models. For example, automated evaluation of tooling or assembly complexity (e.g., component interactions, tolerancing) might be used to assign activity duration times and/or iterative redesign branching probabilities based on historical corporate process data for similar products (as an example, Malhajan [Mahajan 91] has automated estimation of tooling lead times for progressive dies based on feature-based component representations. See also work by Hu [Hu 94]). Other knowledge-based methods might be used for default assignment of resources (people, machines) to activities, or to aid analysis of process bottlenecks. A list of "performable activities" associated with each resource, which contains those activity classes with which the resource can be automatically matched (but not necessarily selected) might also included in a resource representation. Resource representations might also include a measure of productivity rate for each associated activity. Obviously, the usual difficulties with knowledge-based systems - scale-up, knowledge acquisition and updating, coding, etc. - would require a high entry cost for these types of model enhancements.

There may be a role for "critic theory" and debiasing methodologies in PRP modeling to help participants create and evaluate a process model beyond their particular technical focus area and in terms of strategic organizational objectives. In practice, anecdotal evidence suggests that a product manager's decision-making may be strongly biased by his or her particular work background and technical expertise. A manufacturing manager, for example, may push to reduce the test phase on a proof-of-concept model without fully understanding the implications of functional problems which might appear later on in pilot production. A design engineer may assign complex part geometries and excessively tight tolerances, but have little knowledge of the resulting process control difficulties and long tooling lead times. A marketing specialist may change product specifications with inadequate understanding of the often hundreds of costly and time-consuming engineering changes this will precipitate for product and process redesign. There has been some limited work in applying critic theory to design which may merit further investigation for PRP modeling.

One approach to knowledge-based PRP modeling is to consider a *comprehensive* representation of a PRP as a triple (P, A, R), for which P = {p} is the set of product elements, A = {a} is a set of activity classes, and R = {r} is the set of resources available for realization. Each element in each set has in turn certain properties (e.g., p = {s}). These properties denote *hierarchical ordering within each set* (i.e., level of detail) and *mapping between product-activity sets and between activity-resource sets* (Figure 8), as well as other information required for cost, time, and other evaluations. (Variations of this approach have been presented by Cralley [Cralley 89], Duffey [Duffey 93] and others.)

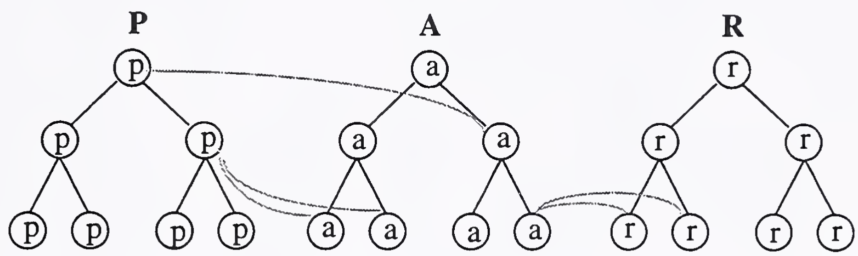

Figure 8: Product Element, Activity Class, and Resource data sets

By convention, classes of product elements **P** in mechanical assemblies can be structured hierarchically by defining each element as a sub-assembly, component, or feature (e.g., a sub-component level element which has both form and functional or manufacturing intent). Resource classes **R** can also be hierarchically ordered similar to a company organization chart for departments of product and manufacturing engineering, tooling, marketing, finance, as well as available outside vendors, prototyping facilities, etc. "Leaves" in this resource tree may be people or machines or some combination of the two. However, a classification scheme for realization activity classes **A** is more problematic than for product elements or resources. For purposes of discussion, a tentative hierarchy of design, prototyping, and other realization activity classes is shown in Figure 9. *Product realization* activities concern the design, building, and evaluation of physical and analytical models prior to production runs. *Production realization activities* concern the tooling and manufacturing ramp-up prior to on-going production. Much activity interdependence occurs between these two groups. *Decision point* activities are the periodic management evaluations which approve and allocate money for successive project stages, and may determine reworking of in-progress product or process designs. The "leaves" of this activity hierarchy tree (see Figure 9) are the smallest units of activities meaningful for development cost and time estimation purposes; that is, those activities for which explicit numbers of machine and human resources, and capital expenditure, can be identified. A separate but interesting discussion of activity taxonomies can be found in work by Malone [Malone 93].

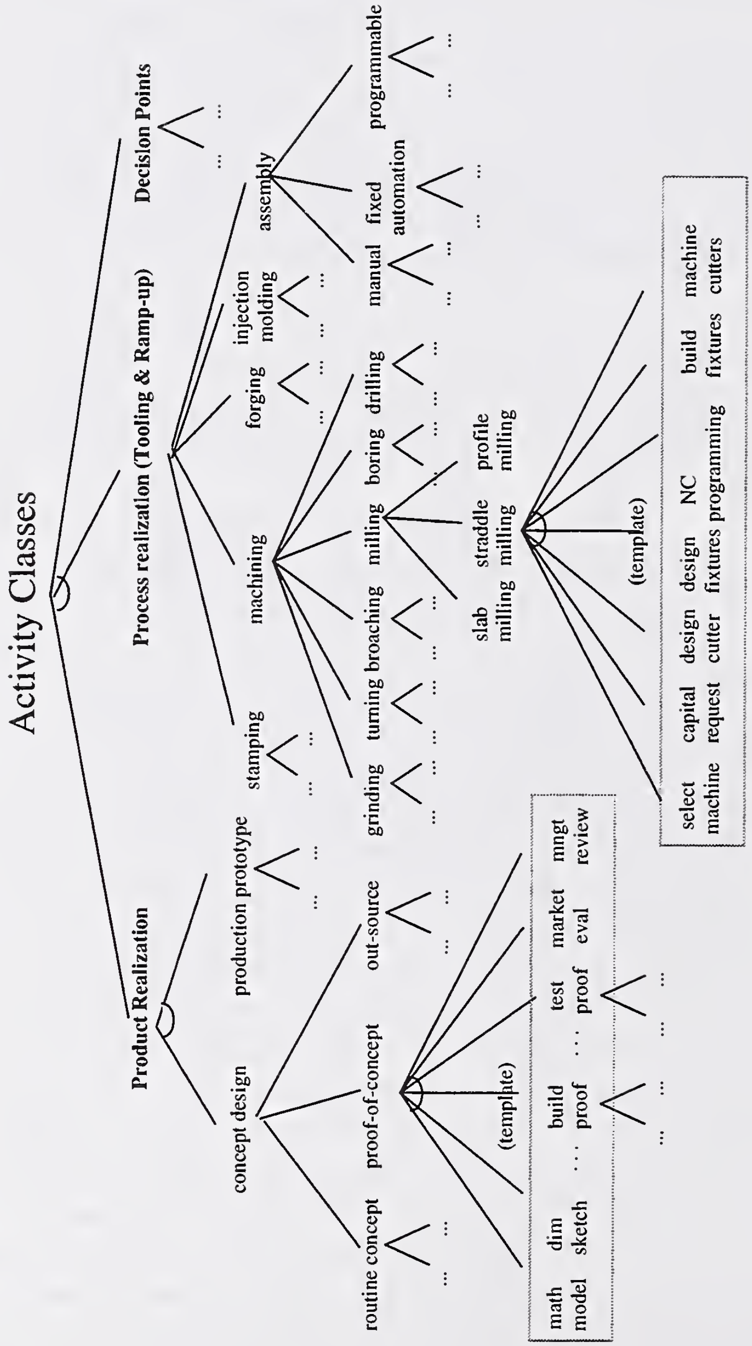

Figure 9: Example hierarchy of activity classes

5. New Methodologies and Software Implementations

5.1 A Petri Net-based Model

A Petri Net-based, object-oriented process modeling software package has been used by NIST researchers in some recent industry test-bed PRP modeling experiments. The following is a discussion of the modeling methods and implementation issues realized in CACE/PM (Computer Aided Concurrent Engineering/ Project Management, hereafter referred to as CACE)[1]. The focus of this section is to highlight generic modeling issues and not issues relating to this specific modeling methodology.

The CACE modeling methodology [Madni 93, Madni 93a] purports to capture, visualize, simulate, and analyze actual or planned PRP's. The representation features multiple levels of abstraction (e.g., an exposition of a hierarchy of tasks, subtasks, and activities within a process), and can be viewed from multiple perspectives (e.g., tasks or resources). The major component of a CACE representation is the process flow (aka control flow) model, which makes use of the so-called Modified Petri Net (MPN) methodology and notation [Madni 88]. As the name suggests, the MPN representational scheme is an adaptation of general Petri nets [David 94, Peterson 81, Reisig 92] which have their roots in the original work of C.A. Petri in 1962. Like a basic Petri net, the MPN is a graphical (but also highly computer-implementable) representation. An MPN graph is made up of four types of primitives: circles, boxes, vertical bars, and directed arcs. Circles represent human or machine-automated processes, tasks, or activities which occur over a period of time, while boxes represent passive "hold" or "wait" states through which process flows can be suspended or synchronized. Vertical bars denote state transitions or events that mark the termination of one activity or hold and the start of another in a flow. Activities or holds are connected to events in an alternating fashion via directed arcs to establish a process control flow sequence, as shown in Figure 10.

MPN's appear to offer a number of properties desirable for PRP modeling, such as the representation of processes with cycles, iterations and choices, in addition to shared resources and interdependencies between parallel or concurrent activities. An MPN graph also offers a hierarchical decomposition similar to IDEF representations in the way that each activity circle within an MPN can be made a "parent tasknet" which points to a "subnet" of sub-activities at a lower level of abstraction. Associated with each activity circle, hold box, and event bar in the MPN is a "frame" through which additional process information can be included about such things as activity durations, resource requirements, knowledge-based rules, and conditional or probabilistic expressions for controlling activity parameters or process flow during simulation. The resources that will be utilized by activities in the course of executing a process can also be incorporated, modeled in a resource hierarchy which exists separately from the MPN. Various resource classes, such as People, Machines, and Tools can be defined, along with multiple subclasses and, ultimately, the actual resource instances that perform process activities. These resource instances are allocated to the activities of a CACE process model by linking them to the appropriate frame(s) in the MPN.

---

1. Certain commercial applications, equipment, instruments, or materials are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

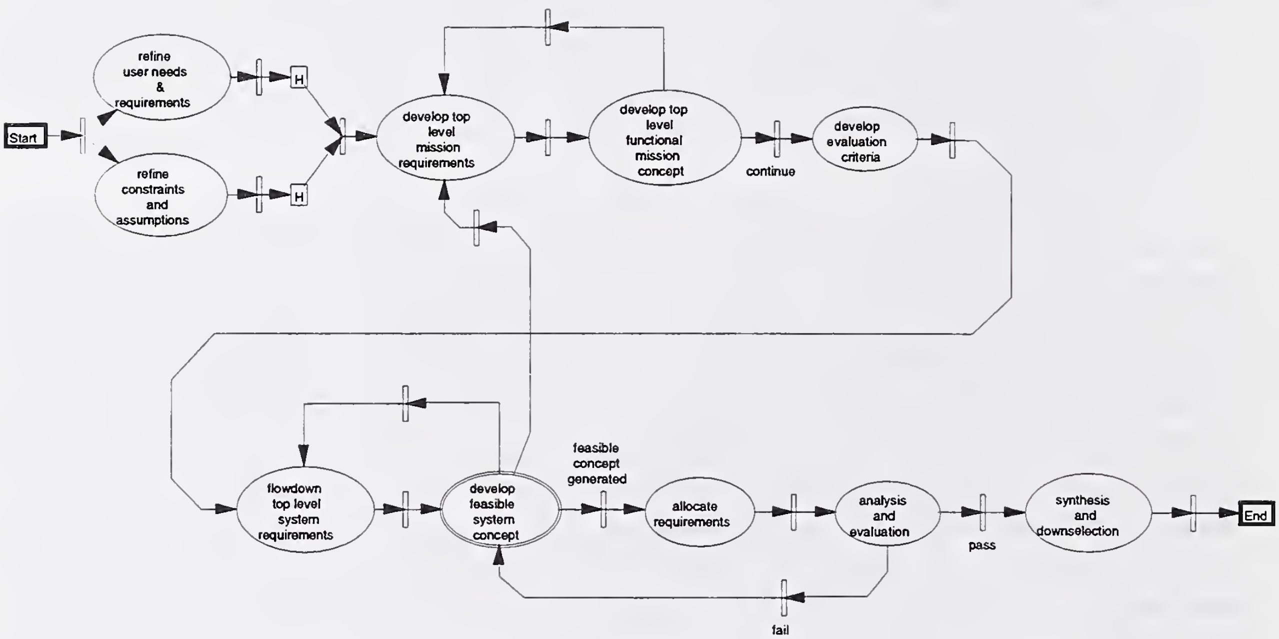

Figure 10: Example of a CACE Tasknet (Process Flow Model)

Once an "as-is" CACE process model has been documented and constructed, it can be executed via a built-in discrete-event simulation routine that can be visualized as a process flow animation. MPN's execute in a fashion similar to "regular" Petri nets by propagating "tokens" (which can be thought of as status markers) through the chain of activities, holds, and events, in a sequence dictated by the layout of the directed arcs, defined activity durations, and any imbedded conditional statements or rules. A token propagates from an input (or "upstream") activity circle (or hold box) to its subsequent output ("downstream") activity if the conditions associated with the event(s) connecting the input and output activities occur, thus causing the transitional event(s) to "fire" and transfer control down the line. Unlike basic Petri net models that use only one kind of token, however, an MPN model utilizes four different color-coded token types for activity circles that denote various activity states - ready, active, done, and "blocked" (i.e., required inputs or resources are not available for activity execution). The software monitors and records the various activity states during process simulation so that such things as resource utilization patterns, conflicts, and process bottlenecks can be identified and analyzed.

CACE simulations can be used as an aid to systematically transform an "as-is" model into a "to-be" improved process model by analyzing and comparing the effects of specific changes in the baseline model. This is partially supported by a "what-if" analysis capability that allows users to define and run simulations of various process scenarios in order to examine the effects of potential improvement options. Simulation output data is stored and can be viewed using CACE's limited battery of simulation-based analyses, including timelines and histograms for activities and resources, event histograms, and aggregate cycle/ throughput time. Cost analysis is not yet part of the current CACE release, although cost rates could be included behind the scenes via use of script commands or user-defined variables.

5.2 DFM Representations and PRP Models (PAR 2)

Design-for-manufacturing research has produced some very good models that guide cost/ quality decisions about product attributes as they affect a stand-alone activity in the product life cycle (e.g., assembly, injection molding, stamping, etc.) [Duffey 90, Dastidar 91]. However, these models generally neglect interdependencies between activities and organizational constraints. To address this, Duffey and Dixon examined PRP representation in a DFM context [Duffey 93]. Their two-stage model (PAR 2), implemented as a proof-of-concept computer tool, addressed preliminary design (prior to detailed design) for mechanical assemblies. In the first stage, two relational matrices are defined which i) link a feature-based product representation to a set of pre-production activity classes, and ii) instantiate activities by linking each selected activity class to an available resource. In the second stage, an activity network is created from these data, and a simulation is run to obtain an aggregate cash flow of preproduction costs for the given design configuration. To provide data for the proof-of-concept implementation, field interviews and product/activity/resource documentation were collected from several manufacturers.

Creation of a product-activity matrix is aided by common subsets of activity classes and their procedural relationships identified in the field research. These activity *templates* can define graph segments which are then connected into the aggregate activity network. In general, such activity templates are more standardized for *process realization* activities than for *product realization* activities. For example, the realization of progressive die tooling has a fairly routine ordering of activities (strip layout, selection of standard die components, layout for die assembly, etc.) that varies very little from one component to another (though the work time required for an activity such as strip layout is highly dependent on part complexity, and may vary considerably). A template for proof-of-concept design, however, may vary tremendously depending on company practice, functional requirements, technology and materials, designer experience, and many other factors.

Figure 11 shows a representation of the *proof-of-concept* "template" from one company with two iteration loops constructed during interviews with design engineers. The inner loop (*minor-proof-change*) typically occurs when minor dimensional changes are proposed after engineering analysis of test results for a proof-of-concept model. In this case, a detail drawing must be revised, tolerances again reviewed by manufacturing, and the other activities inside the loop are "repeated," although often requiring considerably less time than the first iteration. The outer loop (*major-proof-change*) represents redesign efforts required after a review of the proof-of-concept model by upper management, including marketing, production, finance, and other non-engineering evaluations. Typically the decision to redesign for this outer loop requires considerably more effort for each activity in the loop (i.e., a new form or functional concept may be required, or new layout of the subassembly with respect to other subassemblies).

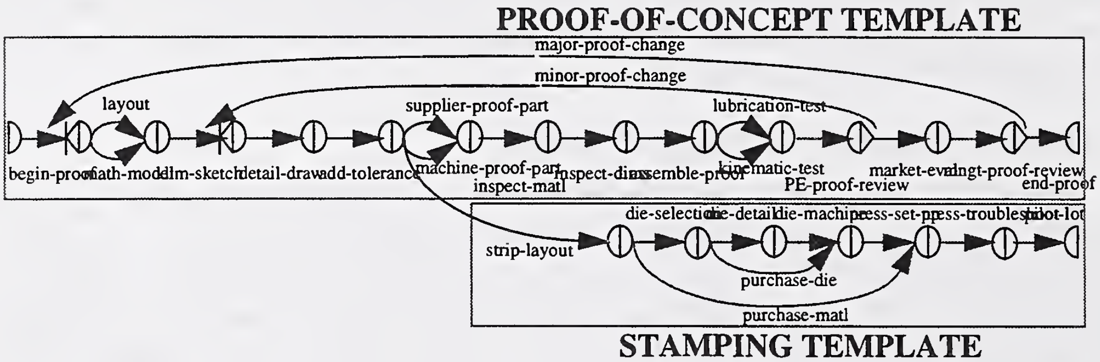

Figure 11: Activity template for proof-of-concept design

Figure 11 also shows an additional template for strip layout and progressive die tooling for a stamped part. When product redesign is required, concurrent process activities such as tooling may also need to be "iterated" to some greater or lesser degree. In some cases, rework for tooling may be relatively insignificant. For example, minor dimensional changes to injection molds are often anticipated, and can be performed with minor remachining and welding operations. For more significant changes of part form, however, entire tool sets may have to be scrapped and the process begun again. Much of the risk evaluation for concurrent product and process design involves assessment of possible redesign activity, and the resulting additional cost and time for tooling rework. For relatively "stable" designs with low-cost tooling, concurrence makes sense; for "unstable" designs and high-cost tooling, linear sequencing of product design and processing activities may actually yield a shorter probable time-to-market. By allowing a design group to explore alternate "overlapping" of templates, and assign time and branching probabilities based on the best available estimates, this model explicitly embodies some of these decision-making trade-offs.

In this model, the time and cost implications of possible design "iteration" and changes in activity concurrency can be examined by varying the model parameters. For example, die design and fabrication for a stamped component can "overlap" testing for a production prototype of its parent subassembly (with increased cost implications if downstream problems occur), or these activities can be assigned sequentially. Because of the explicit relational model for design problem data, aggregate cost and time information can be broken down in many useful ways: by product attribute (for value engineering), by activity class (activity-based costing and overhead assignment), by resource (departmental usage and allocation, scheduling), and by particular cost category (labor, non-recurring, overhead, strategic capital investment, etc.). One interest is how this type of model might potentially integrate feature-based CAD representations with activity-based cost accounting methods.

5.3 Proposed Extensions to IDEF-based Models

Most recently, in part due to increased interest in process modeling and in response to some recognized limitations of the standard IDEF techniques, additional IDEF-based representation schemes such as IDEF3 [IICE 92], IDEF4, IDEF5, and IDEF6 have been introduced as extensions to the original standard IDEF0 and IDEF1X methodologies.

IDEF3, intended as a complementary addition to the standard IDEF0 and IDEF1X methodologies, is primarily a technique for capturing descriptions of the sequences of activities within processes, and as such has potential relevance for PRP modeling efforts. The method involves the capture of information and assessments about the objects that participate in a process, as well as the temporal precedence and causality relationships between the activities and events. As such, IDEF3 adds a missing dimension to the combined IDEF0 and IDEF1 representations. However, IDEF3 employs yet another representation medium of its own in the form of a graphical language that is different from those used in the other IDEF types. The primary graphical entities of this language are UOB (Unit of Behavior) boxes, constraint links, junction boxes, and referents. In an IDEF3 process flow diagram, UOB boxes, representing process activities, actions, or operations, are connected by various types of constraint links, represented by arrows. Solid arrows denote precedence relationships between activities, while dashed arrows depict user-defined relations, and double-headed arrows track the flow of objects. Junction boxes depict the logical structure of a process, including the branching or convergence of process flows, and whether parallel branches are synchronous or asynchronous. Referents can be included to assign additional constraints to junctions for purposes of defining conditions or decision logic for branching or iteration. In addition to the process flow diagram, the IDEF3 representation can be viewed from an object-oriented perspective by means of Object State Transition Network (OSTN) diagrams. These views cut across the process flow network representation and enable descriptions of the objects that participate in or are used or produced by activities, tracking their evolution through a number of process states. These OSTN diagrams are presented in yet another graphical notation, although the methodology provides a cross-referencing between the two IDEF3 representations.

5.4 Process Modeling within STEP

There have been some limited process modeling efforts by STEP (STandard for the Exchange of Product model data) developers. EXPRESS and its graphical notation, EXPRESS-G, is an on-going language development effort within the STEP community for data specification. EXPRESS was developed primarily as an object-oriented *information* modeling, not a process modeling language. However, there have been some efforts to extend EXPRESS for process modeling, though with a focus on physical manufacturing processes [Lapointe 93]. Felser and Mueller [Felser 94] have proposed an extension named EXPRESS-P which uses concepts from the formal language SDL (Specification and Description language) employed for telecommunications systems, and they have described an example application for injection molding. There is evidently considerable effort by industry representatives in the STEP community to include some sort of EXPRESS-based process specification language in EXPRESS version 2. However, "enterprise level" process modeling has been only very tentatively discussed at recent EXPRESS User's Group meetings. There evidently may be some relevant work within the German national standardization body DIN (Deutsche Industrie Norm) for enterprise process modeling, but only a few preliminary working documents in the original language have been produced [Mueller 94]. For related efforts by NIST researchers, see referenced work by Algeo, Ray, and Wilson ([Algeo 94] (a survey of language efforts for physical manufacturing processes) [Ray 92, Ray 92a] [Wilson 91].

5.5 Workflow Modeling in Product Data Management (PDM) Software

There has also been work to integrate PRP modeling concepts with CAD data by commercial developers of Product Data Management (PDM) software. Puttre [Puttre 94] describes the introduction of "workflow software" by Unigraphics, Sherpa, Parametrics, and other companies to help track documents as they move through the product development cycle. Many companies also have significant internal efforts in this area. For example, Lockheed Missile and Space Corp. (LMSC) claims that their engineering data management system for the Thaad missile program can now archive their product development process in considerable detail, including both review processes and efforts of distributed design teams [Wallace 94]. However, there is also skepticism about the claims of vendors for implementing "workflow automation" unless legacy data systems and corporate cultures are fundamentally changed [Levine 94].

5.6 Systems Engineering Software for Product Development Processes

Some large-scale aerospace projects use one of several commercial systems engineering software packages with capabilities related to process modeling. Systems such as these are used to help create and track the flowdown of functional design requirements into system components, task requirements, resources, and document generation. These packages have not yet been examined by the authors.

6. Industry PRP Modeling Collaborations

In the course of this preliminary study, NIST staff and associated researchers have participated in several recent industry exercises to build PRP models and examine existing industry methodologies. Some are discussed below.

6.1 Process Modeling for Missile Seeker System

This case study was conducted for several reasons, with the overall goal of reducing the cycle time to develop prototype defense systems. It involved researchers from two defense industries, several federal agencies (civilian and military), and technical consultants (IDA, Institute for Defense Analysis). Process information was drawn from current processes used at two leading missile developers. Prior to development of the PRP model a scenario was developed defining the initial design constraints that were to be addressed in developing a "brassboard" missile seeker system. These initial constraints assisted in limiting the scope of the project and in ensuring conformance of initial starting conditions for the two companies. Information used in the model was collected (through discussions, presentation materials, project management PERT charts, organizational descriptions, etc.) at meetings held at the manufacturing site as well as through normal channels such as telephone, mail, email, etc. The industrial representatives also assisted in defining how the PRP models should be constructed to best represent the methods employed at the site. The models were created using a tool developed by Perceptronics called CACE/PM (Computer-Aided Concurrent Engineering/Process Modeler). To exploit certain functionality of the CACE/PM tool, information was sought on iterations, resources used to complete activities, and activity duration distributions. Only conditional (not probabilistic) branching was specified for the case studies in order to provide consistent, determinable results that would aid in evaluation of the models. The model started at the receipt of contract specifications and finished at the fabrication of prototype components and subsystems.

To compress the time frame for the project it was decided to utilize the extensive information available from the companies related to project management (e.g., existing PERT models). This provided a basis to develop early "draft" models that were used to enhance data collection during the site visits. During interviews the draft models assisted the research team in quickly focusing from a high level view to the area of interest for the engineer being interviewed. At this point the engineer would redline the model and key discussion was captured in notes (i.e., organizational issues, recommended procedure vs. actual, etc.). To meet the scoping constraints, the model was completed in significantly more detail in only two subsystem areas identified at start of project. This allowed for an overall high level model to be constructed, yet also achieve the objective of exploring more specific, detailed aspects of PRP modeling.

From the case study, several issues were identified that significantly impact how model development proceeds. For example, organizational structure can have significant effects on the development of a PRP model. Inherent within well-established organizational structures are imposed constraints that can strongly drive how process models are constructed. For organizations that are undergoing a major restructuring or re-engineering of the enterprise, the organizational impact on model construction is often less consequential. With smaller scoped re-engineering efforts this is usually not the case and models will tend to follow guidelines established to conform to organizational infrastructure. In many cases this organizational infrastructure is perceived as providing the competitive edge for companies in responding to customer requests. Another finding was that to initiate a modeling effort it is very useful to start with existing process information for assisting in model creation. This can help "jump start" the modeling effect yet can also have some unanticipated and potentially significant effects. Often the most useful documentation are PERT charts used for project management. Although these materials help reduce the time in generating a model there is some concern that it can bias a PRP model by filtering the intended enterprise view with a project management perspective. It is difficult to surmise the impact of biasing PRP models with PM information. How the PRP models are to be used and what results are required will dictate what information should be used for model creation.

6.2 Process Modeling for Mid-sized Scientific Satellites

Managers at the NASA Goddard Space Flight Center are examining new process modeling tools to help "re-engineer" the mission life cycle for a new series of mid-sized scientific satellites. A fairly complex (though static) model of the generic NASA project life-cycle currently exists as a large paper diagram which has the following top-level phases:

Pre-Phase A: Advanced Studies
Phase A: Preliminary Analysis
Phase B: Definition
Phase C: Design
Phase D: Development
Phase E: Operations

NASA managers are interested in revising both the underlying processes and improving the tools to model them (we have represented parts of this process at NIST using a Petri Net-based modeling tool). As with the missile seeker project described above, the overriding goal is to reduce overall cycle time for each satellite mission. Several design process improvements have been suggested, such as early simulation and testing of power subsystems that must meet demands of multiple, independently-designed and built scientific instrument packages. They also want to explore programmatic process improvements, such as the complex and lengthy review process for proposed experiments to include on each given mission. The proposed modeling approach is based on "functional analysis" which is defined by one NASA manager as;

> A method of applying a topology to a process (or series of processes) in order to derive an understanding of relationships between elements of that process; and further to provide a structure which is used to allocate those elements for physical implementation.

This manager defines three tools of functional analysis which will be necessary for any advanced modeling tool for practical use at NASA:

1) The functional flow block diagram (FFBD): a logical interaction between functional elements.
2) The requirement allocation sheet (RAS): a verbal expansion of an individual function, its associated performance limits (requirements) and which physical element of the system will implement it.
3) The timeline sheet (TLS): A pathological "walk through" of an FFBD to create a best guess estimate of events vs. time.

It has been suggested that this approach to process modeling may be best embodied in systems engineering software discussed in Section 5.6. We are currently examining these modeling paradigms, and their relationship to other PRP tools in this study, in collaboration with NASA personnel.

6.3 Other Industry Process Modeling

Also in the course of this study, several site visits and discussions were conducted with other industries. Engineering managers identified strong internal needs for improving and standardizing their process modeling activities. Documentation on several current industry PRP modeling practices were collected, and there has been a strong interest in future collaboration.

7. Other Applications for PRP Models

The focus of this report has been on PRP models as an aid to decision-making at the early design stage. However, PRP modeling tools also have potential for other applications just beginning to be addressed in industry practice or research. Several (discussed below) include:

- Process archiving after project completion
- Training and education applications
- Bidding processes
- Real-time process execution

Process archiving. Recently, it was reported in the news media that much of the design process knowledge for the Saturn V program has been lost due to poorly stored documentation, deaths of key participants, etc. Prototyping, testing and fabrication processes at the time did not use today's microelectronics, and were in many ways different from current practices. Retired NASA engineers speculated that the Apollo moon launch could not be repeated today even if funding was available. New PRP archiving methods might use activity networks as a procedural context for multi-media such as video clips of prototypes and design review meetings, direct linkage to FE analysis results, CAD files, routing sheets, etc. For example, consider the value of an "archived" process model which includes video clips of prototype failure modes, fabrication processes, and commentary by key personnel on design issues.

Training. Process models and related engineering design concepts are also potentially relevant to training in a "high performance workplace" [Duffey 94a]. Ideally, an integrated model of processes in an organization can draw attention to the goals and ambitions of the firm as a whole in ways that may not be noticeable to people as they go about their day-to-day business. Currently, "hard copy" process modeling diagrams are commonly used for training engineers and managers in many firms (both NASA and Xerox reported interest in adapting new PRP modeling methods for training new engineers). However, recent advances in user interface and simulation methods also make them extremely effective as training tools for line workers. There are two challenges to integrating process modeling tools into a training environment: 1) enable the "naive" user of such models (the employee/student) to simulate workplace decisions and see their downstream consequences while keeping the underlying representational complexity of the simulation transparent. 2) integrate the process model in a multimedia context of video images, CAD images, etc. For example, consider an activity network that includes probabilistic branching. As the student is "walked" through design and production activities with a sequence of multimedia images and given different tasks/lessons, a random path generator determines whether or not a virtual part the student created is out of tolerance, and therefore must be returned to a heat treatment department for rework. Using probabilistic branching, each student's walk through a production process would be unique and randomly affected by different common workplace problems. Integration of process models with recent learning technology ideas, such as scripting and "drive to failure" concepts of pioneered by Roger Schank and Anderson Consulting [Williamson 94] might merit further investigation.

Bidding. One major initiative to use process models for bidding applications at a large aerospace manufacturer was reported to the authors during preparation of this report. Also, using simulation of process models for cost and schedule uncertainty is under investigation for decisions about bid pricing and contract terms in domains such as commercial shipbuilding. There exists a body of academic research in this area [Elmaghraby 90], but its extension to industry practice has not been explored. One related, on-going study is investigating process simulations to generate a cost probability distribution to aid bidding decisions for "special" jobs at a mid-sized gear manufacturer [Duffey 94b].

Real-Time Process Execution. Motorola has been participating in an ARPA-sponsored project to use Petri net-based process modeling software for applications such as alerting engineers' "beepers" when computer analysis runs are completed or prototype testing resources become available.

8. Other Research Related to PRP Modeling

Research that is relevant to PRP modeling but beyond the scope of this report can be found in many different academic disciplines (e.g., computer science, mechanical engineering, operations research, management science). A few studies are mentioned below.

8.1 Task Partitioning

There are several interesting PRP analysis techniques which might be integrated in future PRP modeling tools. For example, one *task partitioning* technique addresses "design interactions," a term used by Whitney to:

> express complexity, not in the sense that particular design tasks are difficult but rather that they affect each other in circular ways that are difficult for designers to detect and managers to control [Whitney 90, p.11].

Whitney noted that while design tools are increasingly available for component realization (CAD, FEM), fabrication (CNC), and some system realization (bond graphs, kinematic simulators), he could find only one proposed tool for managing design task interactions. Known as the Steward diagram [Steward 81], this simple technique helps to identify efficient sequencing of design tasks, and has been tentatively investigated for estimating development time [Rogers 89, Eppinger 90]. In the Steward diagram (also called a "design structure matrix"), design tasks are first assigned as row and column labels of a "precedence" matrix in an arbitrary sequence (identical for both rows and columns). Binary elements of the matrix indicate dependency where information from a column task is required to complete a row task. Positive elements in the upper right diagonal of the matrix indicate coupling between tasks in the given sequence, while elements in the lower triangle indicate no coupling. Several methods have been explored to reorder (partition) the task sequence to minimize coupling and identify the remaining "blocks" of interdependent tasks. Within the remaining blocks, algorithms have also been devised which attempt to minimize iteration by selecting the best subsequence for the coupled tasks (termed "tearing" the selected elements from the matrix to initiate iteration). A somewhat related method that can evaluate task partitions in terms of "linkage intensity" was developed by Yuang and Raz [Yuang 1992], and other research [Bell 92] which points towards evaluation methods for process complexity.

Eppinger [Eppinger 90] has developed some interesting variations on the Steward partitioning algorithm. By using numerical elements and vectors instead of binary elements, Eppinger explored how the informational content of the matrix could be enhanced not only for dependency, but also task duration, physical adjacency, and certainty of information. However, there remain some limitations to the design structure matrix as an underlying model for a management tool. First, while experiments have been conducted using both management-defined abstract task descriptions ("task-level") and designer-defined parameter-selection tasks ("parameter-level"), there is no existing mechanism to integrate or even consistently define these multiple levels of detail. Second, the design structure matrix is only a "static" representation of tasks, and there is no explicit connection between those tasks and the associated product attributes or resources in the design process. This makes it difficult to examine how task sequence would be affected by modifications to the product model, or an alternate allocation of resources. Third, while schemes to use the design structure matrix to examine the relative sensitivity of development time to task partitioning have been proposed, the actual estimation of development time, let alone development cost, has not yet been addressed. Future attempts to estimate cost and time from a design structure matrix may be limited by its ability to represent and manipulate complex and often qualitative information within its vector elements. Other interesting research related to Steward's task partitioning work can be found in work by Kusiak [Kusiak 93].

8.2 Propagation of Design Errors

Clausing states that the cost and time of prototype-building and other downstream activities are heavily dependent on the product design's "robustness" as established in the early design stage:

> In the best process, when robustness has been developed early concurrently with the design of the product, the only remaining activity after the design has been completed and robustness verified is to concentrate totally upon the elimination of mistakes from the design. There are literally millions of design decisions, and even those decisions where experience is sufficient will still have some mistakes, because even a very tiny error rate, applied to the huge number of decisions, will still result in hundreds of errors. [Clausing 90, p. 18]

In general agreement with Clausing, Bailey at Xerox has suggested a model of activity interdependency in terms of downstream propagation of design errors and their influence on development time [Bailey 89]. He has identified three types of inputs for a design activity: specifications, technology, and standards. Each has its own associated error type. An unnecessarily precise weight specification for a photocopier might result in an inadequate counter-balance mechanism designed downstream. Designers of a new paper-feeding technology might neglect to specify a feed belt stiffness, resulting in several prototypes before a required value was chosen instead of being defined by other design choices. One serious type of standards error might be when a metric screw is specified but, unknown until production ramp-up, it is unavailable from a supplier. (Note that, in the nomenclature of Eppinger's model, these are "parameter-level" design activities, but they have great bearing on "task-level" iterations in the development process.)

Bailey's model views the design process as iteration of design/build/test activities which continue until the product design "stabilizes" enough to begin production ramp-up. Errors may be due to the input errors described above or due to problems that occur during design computations within a given iteration. A small simulation to test his model requires input values for initial design error rate, design activity error rate, test efficiency, and design complexity (expressed as the number of inspectable dimensions). The output is the expected number of prototypes prior to production ramp-up.

8.3 Conversion Between Process Representations

Industry demand for conversion algorithms between different computer-based process representations will probably increase significantly just as CAD file conversion routines have become a persistent (and still poorly met) demand of industry users in the last fifteen years. Vendors of IDEF-based software are trying to provide output capabilities for both popular project management software and simulation software. From the other end, at least one well-known simulation software vendor (CACI) has attempted to develop routines to input legacy IDEF models for its proprietary activity network representations. Beyond these vendor-specific efforts, only one conversion research project was identified. Elmaghraby at North Carolina State has an on-going (but still unpublished) project for conversion of Petri net models into a generalized activity network (GAN, see [Elmaghraby 77]) model for use in SLAM-based software. He contends that Petri net models are the easiest to build but difficult to analyze, while the opposite is true for SLAM-type models, and proposes a marriage between the two representations.

9. Summary

This report has tried to present a "bottom up" introduction to PRP modeling requirements and practices in industry which should drive new methods and computer tools. Practitioners and researchers of PRP models come from diverse communities such as systems engineering, computer science, mechanical engineering, and management science. These communities have very different modeling paradigms and the survey we conducted, though far from comprehensive, is at least representative of this diversity. Because PRP modeling is such a new and burgeoning field, there is likely important research that we have not uncovered. Also much of the "best practice" in PRP modeling appears to be internal to corporate manufacturing and has not been disseminated. Beyond U.S. corporate practices and methods, there are also likely foreign advances in PRP modeling that are unknown to U.S. practitioners and researchers. We have also tried to identify directions for future research in PRP models in areas such as knowledge-based process representations, simulation, and economic modeling.

10. References

[Algeo 94] Algeo, M.E., "A State-of-the-Art Survey of Methodologies for Representing Manufacturing Process Capabilities," National Institute of Standards and Technology Internal Report (NISTIR 5391), March 1994.

[Bailey 89] Bailey, John. "Introduction to the Design Quality Modeling Concept," Xerox Corporation memorandum and private communication. May 1989.

[Bell 92] Bell, David G., Srikanth M. Kannapam, Dean L. Taylor. "Product Development Process Dynamics," *Design Theory and Methodology*. DE-Vol. 42, ASME 1992.

[Bloch 92] Bloch, Carl, and Ranganathan, Ranga, "Process-Based Cost Modeling," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 15, no. 3, June 1992.

[Bonini 63] Bonini, Charles P. Simulation of Information and Decision Systems in the Firm. Prentice-Hall, Englewood Cliffs, NJ: 1963.

[Busby 93] Busby, J.S. and G.M. Williams. "The value and limitations of using process models to describe the manufacturing organization." *Int. J. Prod. Res.*, vol. 31, n. 39, 2179-2194. 1993.

[Clark 89] Clark, Kim, and Fujimoto, Takahiro. "Overlapping Problem-Solving in Product Development," Managing International Manufacturing. Elsevier Science Publishers, New York: 1989.

[Clausing 90] Clausing, Don, Concurrent Engineering Design Clinic, Society of Manufacturing Engineers, Yipslanti, MI, June 7, 1990.

[Cook 91] Cook, Harry E., and DeVor, Richard E. "On Competitive Manufacturing Enterprises: The S-Model and the Theory of Quality," *Manufacturing Review*, vol. 4, no. 2, June 1991.

[Cralley 89] Cralley, William E. and Tse, Edison. "Management of Risk and Uncertainty in Product Development Processes," Institute for Defense Analyses Paper P-2153, June 1989.

[Dastidar 91] Dastidar, Pratip. "A Knowledge-Based Manufacturing Advisory System for the Economical Design of Metal Stampings." Ph.D. Dissertation, Department of Mechanical Engineering, University of Massachusetts at Amherst: May 1991.

[David 94] David, Rene, and Alla, Hassane, "Petri Nets for Modeling of Dynamic Systems - A Survey," *Automatica*, vol. 30, no. 2, pp. 175-202, 1994.

[Davison 93] Davison, William R., United Technologies Research Center. Private communication, November 1993.

[De Wit 90] De Wit, J. and Heeroelen, W.S. "An Evaluation of Microcomputer-Based Software Packages for Project Management," European Journal of Operations Research, no.. 48.

[Duffey 90] Duffey, Michael R., and Dixon, J.R. "A Program of Research in Mechanical Design: Computer-Based Models and Representations," *Mechanism and Machine Theory*. Vol. 25, No. 3. 1990.

[Duffey 93] Duffey, Michael R., and Dixon, J.R. "Managing the Product Realization Process: A Model for Aggregate Cost and Time-to-Market Evaluation," *Journal of Concurrent Engineering: Research and Applications*, no. 1, vol. 1, 1993.

[Duffey 94a] Duffey, Michael R. and Lyons, Kevin "Adult Technical Learning: Engineering Design Models for the High Performance Workplace," White Paper for Workshop on Learning Technologies, NIST Advanced Technology Program, October 24-25, 1994.

[Duffey 94b] Duffey, Michael R. and Anderson, Richard C. "Cost Variability in the Job Shop Environment," presentation at the Fifth Annual Meeting of the Production and Operations Management Society. Washington, DC: October 8-11, 1994.

[Elmaghraby 77] Elmaghraby, S.E. Activity Networks: Project Planning and Control by Network Models. John Wiley & Sons, New York: 1977.

[Elmaghraby 90] Elmaghraby, S.E. "Project Bidding Under Deterministic and Probabalistic Activity Durations," *European Journal of Operations Research*, no. 49, 1990.

[Elmaghraby 94] Elmaghraby, S.E. "Activity Nets: A Guided Tour Through Some Recent Developments," OR Report No. 282, Department of Operations Research, North Carolina State University, May 1994.

[Eppinger 90] Eppinger, S.D., Whitney, D.E., Smith, R.P., and Gebala, D.A. "Organizing the Tasks in Complex Design Projects," *Proceedings of the ASME Design Automation*

Conference. Chicago: Sept. 1990 (Extended version is Working Paper WP# 3083-89-MS, Sloan School of Management.)

[Felser 94] Felser, Winifred and Wolfgang Mueller. "EXPRESS-P: Extending EXPRESS for Process Modeling and Monitoring," *Proceedings of the 1994 ASME Computers in Engineering Conference*, Minneapolis, MN, September 11-14, 1994.

[FIPS 183] Integration Definition for Function Modeling (IDEF0). Federal Information Processing Standards (FIPS) Publication 183, National Institute of Standards and Technology, December 21, 1993.

[FIPS 184] Integration Definition for Information Modeling (IDEF1X). Federal Information Processing Standards (FIPS) Publication 184, National Institute of Standards and Technology, December 21, 1993.

[Gold 92] Gold, Steven C., "Modeling Short-Run Cost and Production Functions in Computerized Business Simulations," *Simulation and Gaming*, vol. 23 no. 4, December 1992.

[Haffner 88] Haffner, Eric W., and Graves, Robert J. "Managing New Product Time to Market Using Time-Cost Trade-Off Methods," *International Journal of Management Science*. pp. 117-124, Vol. 16. No. 2., 1988.

[Haines 90] Haines, Lewis A., and Evers, Ken., "An IDEF0 Representation of the Instructional System Development (ISD) Process - Why it Works," IEEE Publication, 1990.

[Hoover 89] Hoover, S. V., and Perry R. F. Simulation , Addison Wesley, Reading, MA, 1989

[Hu 94] Hu, Weiyi. "Process Selection for Assembled Products Based on An Overall Evaluation of Cost, Time, and Performance," in-progress Ph.D. dissertation, Department of Mechanical Engineering, University of Massachusetts at Amherst.

[Huseby 93] Huseby, Arne Bang and Tosseviken, Kristin. "Optimal Project Management Policies - A Bayesian Approach," technical paper, University of Oslo, Norway. 1993.

[ITI 94] Industrial Technology Institute. Miscellaneous documentation and presentation materials on TACOM Supply Chain Integration Pilot Project, February 1994.

[IICE 92] Information Integration for Concurrent Engineering (IICE) IDEF3 Process Description Capture Method Report. Air Force Systems Command, Wright-Patterson AFB, OH, May 1992, Knowledge Based Systems, Incorporated.

[ICAM 81] Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II: Volume IV - Function Modeling Manual (IDEF0). Air Force Materials Laboratory, Wright-Patterson AFB, OH, (DTIC-B062457), June 1981. SofTech, Inc.

[ICAM 81a] Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II: Volume V - Information Modeling Manual (IDEF1X). Air Force Materials Laboratory, Wright-Patterson AFB, OH, (DTIC-B062457), June 1981. SofTech, Inc.

[Kusiak 93] Kusiak, A., and Wang, J., "Decomposition of the Design Process," *Journal of*

Mechanical Design, Vol. 115, December 1993.

[Kusiak 94] Kusiak, A., Larson, T.N., and Wang, J. "Reengineering of Design and Manufacturing Processes," *Computers ind. Engng*, Vol. 26, No. 3, pp 521-536, 1994.

[Lapointe 93] Lapointe, Linda J., Thomas J. Laliberty, Robert V.E. Bryant. "System Description Document for the Manufacturing Optimization System," Raytheon Company report for ARPA Order No. 8363/02, July 1993.

[Levine 94] Levine, Lawrence O. and Aurand, Steven S. "Evaluating Automated Workflow Systems for Administrative Processes," *Interfaces*, vol. 24, no. 5. September-October 1994.

[Madni 88] Madni, Azad M., "HUMANE: A Designer's Assistant for Modeling and Evaluating Function Allocation Options," *Ergonomics of Hybrid Automated Systems I*, Elsevier Science Publishers B. V., Amsterdam, 1988.

[Madni 93] Madni, Azad M. Process Modeling with CACE/PM: Methodology and Notation. Presentation to IRFPA Integration into Seeker Modeling Meeting, August 17, 1993.

[Madni 93a] Madni, Azad M., "Computer-Aided Concurrent Engineering for DARPA Initiative in Concurrent Engineering (DICE): Methodology and Tools (Phases 4 and 5), Final Technical Report," Advanced Research Projects Agency, Arlington, VA, November 24, 1993.

[Mahajan 91] Mahajan, Prashant V. "Design for Stamping: Estimation of Relative Die Cost for Stamped Parts." Master's Thesis, Department of Mechanical Engineering, University of Massachusetts at Amherst: March 1991.

[Malcolm 59] Malcolm, D.G., Roseboom, J.H., and Clark, C.E. "Applications of a Technique for Research and Development Program Evaluation," *Operations Research*. Vol. 7, No. 5, 1959.

[Malhotra 92] Malhotra, Rajeev and Sundaresan Jayaraman. "An Integrated Framework for Enterprise Modeling," *Journal of Manufacturing Systems*, vol. 11, no. 6, 1992.

[Malone 93] Malone, Thomas W., Kevin Crowston, Jintae Lee, and Brian Pentland. "Tools for Inventing Organizations: Toward a Handbook of Organizational Processes," *Proceedings of the 2nd IEEE Workshop on Enabling technologies Infrastructure for Collaborative Enterprises*, Morgantown, WV, April 20-22, 1993.

[Marran 89] Marran, L. and M.S. Fadall, A New Modeling Methodology for Large Scale Systems, CH2809-2/89/0000-0989, IEEE, 1989

[Peterson 81] Peterson, James L. Petri Net Theory and the Modeling of Systems. Prentice-Hall, Englewood Cliffs, NJ, 1981.

[Pritsker 66] Pritsker, Alan, and Happ, William. "GERT: Graphical Evaluation and Review Technique," *Journal of Industrial Engineering*, Vol. 17, No. 5, May 1966.

[Puttre 94] Puttre, Michael. "Taking Control of the Desktop: Workflow Software and Product Data Management Systems," *Mechanical Engineering*, September 1994.

[Ray 92] Ray, Steven. "Using the ALPS Process Plan Model," *Proceedings of the ASME Manufacturing International Conference*, Dallas, TX, 1992.

[Ray 92a] Ray, Steven R. and M. Kate Senehi. Data Map Workshop for Manufacturing Data. National Institute of Standards and Technology Internal Report (NISTIR 5160), May 1992.

[Reimann 94] Reimann, Michael D., "A Methodology for Quantitative Assessment of the Impact of Alternative Business Practices on System Life-Cycle Costs," paper presented to the Society of Cost Estimating and Analysis 1994 National Conference, June 22, 1994.

[Reisig 92] Reisig, Wolfgang. A Primer in Petri Net Design. Springer-Verlag, Berlin, 1992.

[Rogers 89] Rogers, J.L., and Padula,, S.L. "An Intelligent Design Advisor for the Design Manager," NASA TM 101558. February 1989.

[Smith 90] Smith, Preston G. "Fast-Cycle Product Development," *Engineering Management Journal.* Vol. 2, No. 2, June 1990.

[Smith 91] Smith, Preston G. Developing Products in Half the Time. Van Nostrand, Reinhold, New York: 1991.

[Son 92] Son, Young K. "Simulation-Based Manufacturing Accounting for Modern Management," *Journal of Manufacturing Systems*, vol. 12, no. 5, 1992.

[Steward 81] Steward, D.V. "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Transactions on Engineering Management*. pp. 71-74, Aug. 1981.

[Stewart 87] Stewart, Rodney B. and Wyskida, Richard M. Cost Estimator's Reference Manual. John Wiley, New York: 1987.

[Ulrich 91] Ulrich, Karl T., Sartorius, David, Pearson, Scott, and Jakiela, Mark. "A Framework for Including the Value of Time in Design-for-Manufacturing Decision Making," MIT Working Paper #3243-91-MSA. Cambridge, MA: Feb. 1991.

[Wall 91] Wall, Matthew B., Ulrich, Karl T., and Flowers, Woodie C. "Making Sense of Prototyping Technologies for Product Design," *Design Theory and Methodology*. DE-Vol. 31, ASME 1991.

[Wallace 94] Wallace, Scott. "Accelerating Engineering Design," *Byte*, July 1994.

[Watts 84] Watts, F. "Engineering Changes: A Case Study," *Production and Inventory Management*, Fourth Quarter, 1984.

[Whitney 90] Whitney, Daniel E. "Designing the Design Process," *Research in Engineering Design*. Springer-Verlag, New York: 1990.

[Whitney 94] Whitney, Daniel E., Nevins, James L., DeFazio, Thomas L., Gustavson, Richard E., "Problems and Issues in Design and Manufacture of Complex Electro-Mechanical Systems," Publication of Draper Laboratory, Cambridge, MA, 1994.

[Williamson 94] Williamson, Mickey, "High Tech Training," *Byte*, December 1994.

[Wilson 91] Wilson, P., "Modeling Languages Compared: EXPRESS, IDEF1X, NIAM, OMT and Shlaer-Mellor," Rensselear Design Research Center Technical Report no. 91015, May 1991.

[Wisnosky 90] Wisnosky, Dennis E., and Batteau, Allen W. "IDEF in Principle and Practice," *Gateway*, May/June 1990, pp 8-11.

[Wisnosky 94] Wisnosky, D., "How Did the Japanese Do It?," Quarterly Newsletter of Wizdom Systems, Winter 1994.

[Wood 89] Wood, K.L., and Antonsson, E.K. "Computations with Imprecise Parameters in Engineering Design: Background and Theory," *ASME Journal of Mechanisms, Transmissions and Automation in Design*. March, 1989.

[Yuang 92] Yuang, A. and T. Raz, "Linkage Analysis of Processes," *Software - Practice and Experience*, vol. 22(10), October 1992.