CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

The Virtual Team Alliance (VTA): An Extended Theory of Coordination in Concurrent Product Development Projects

By

Jan Thomsen, Martin A. Fischer, and Raymond E. Levitt

CIFE Working Paper #44
March, 1998

STANFORD UNIVERSITY

If you would like to contact the authors please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University,
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

The Virtual Team Alliance (VTA): An Extended Theory of Coordination in Concurrent Product Development Projects[1]

JAN THOMSEN, MARTIN A. FISCHER and RAYMOND E. LEVITT
Construction Engineering and Management,
Department of Civil and Environmental Engineering,
Stanford University, Stanford, CA 94305-4020

Abstract

As organizations strive to shrink time-to-market for their complex products, they find traditional project management concepts and tools lacking in several ways. Fast-paced product development requires that many interdependent activities be performed concurrently. However, Critical Path (CPM) models ignore relationships between parallel activities, assuming them to be independent. Moreover, the CPM model treats participants like any other "check-out" resource. Thus, CPM models cannot predict the effect of differing participant profiles on project performance. Organizational analysis tools like the Virtual Design Team (VDT) model participants as information-processing entities with skill sets and experience, and explicitly model lateral interdependencies between activities. With these extensions, VDT offers powerful new capabilities for modeling and analyzing fast-paced work processes and the project teams that execute them. VDT assumes that all project participants have congruent goals and makes assumptions about the routineness of the activities themselves that restrict its applicability to relatively routine work processes. Given the less routine, fast-paced nature of many high-tech product development efforts, these representations no longer adequately capture how project participants coordinate their work. Using previous VDT work on organizational simulation and a retrospective case example drawn from an offshore field development project, we describe extensions to the VDT representation. We represent project participants as teleological professionals, and explicitly model goal incongruency between them. By modeling activity complexity, flexibility, uncertainty, and interdependence strength, our work process representation captures the effects of goal incongruency on the performance of semi-routine, fast-paced projects.

Key Words and Phrases: Computational Organizational Theory, Contingency Theory, Coordination Theory, Engineering Management, Goal Incongruency, Information Processing, Organizational Design.

1. Introduction

Product development cycles are becoming increasingly shorter. As a result, organizational designs that were suitable for routine work in placid environments no longer fit most fast-paced projects (Brown and Eisenhardt, 1997; Mohrman *et al.*, 1995, p. 11). The design of efficient and effective work processes for fast-paced projects is

---

[1] The National Science Foundation, Transformations to Quality Organizations program, Grant SBR-9422389 and a grant from Det Norske Veritas as part of the Networked DNV project supported this research.

tricky. As product development becomes more integrated and collaborative, coordination and communication between project team members has become a more significant component of the development activity. Traditional project planning tools, such as Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT), assume an ideal situation in which parallel activities for different parts of the project deliverable are independent and uncoupled (Moder *et al.*, 1983). However, most complex tasks necessary to the production of an artifact cannot be decomposed into totally independent activities—only partially independent activities (Simon, 1996, pp. 197-204). While CPM and PERT model sequential dependencies through explicit representation of precedence relationships between activities, they do not account for information interdependencies between concurrent activities and fail to address the impact of project team members' interactions on project performance. In this paper, we operationalize representations of project participants and work processes to overcome these shortcomings.

Engineering management techniques, such as the Design Structure Matrix (DSM) (Eppinger *et al.,* 1994; Steward, 1981), represent interactions between activities in order to identify "blocks" of independent activities, such as conceptual design, detailed design, procurement, and assembly. However, in fast-paced design projects most activities occur in parallel, and it is difficult to construct a DSM matrix because DSM requires that activities be listed sequentially along both axes of the matrix. More importantly, though, the DSM matrix does not aid us in finding an answer to the more interesting questions of why particular interdependence relationships exist and how these relationships influence the coordination between project team members. To remedy these shortcomings, computational organizational analysis tools, such as the Virtual Design Team (VDT) (Jin and Levitt, 1996), focus attention on the design work process and the way in which communication and coordination affect work processes. VDT is based on the premise that coordination work takes time and can delay project completion, increase costs, and affect work process quality.

VDT combines the CPM/PERT modeling approaches and concepts from DSM with organizational theory. VDT was developed to simulate routine design activities—well-understood processes in which there is very little doubt about the nature of the specific sub-tasks that are required to complete the activities or how they will be executed. For many of today's less routine projects, it is still possible to pre-enumerate the activities that must be done; however, there is now more flexibility in carrying out these activities Many fast-paced projects operate at the edge of what is known—and therefore programmable. Our information-processing model supports the representation of work process versatility necessary for project teams to find solutions[2] to tightened project goals for less routine projects. At the same time, our model avoids the enormous information requirements and complexity of decision-theoretic or utility-based representations of design projects (Howard and Matheson, 1983).

VDT assumes that all actors who are working on a project have both similar goals and similar approaches to problem solving. However, engineering and management professionals involved in multidisciplinary project teams clearly differ in regard to what they think is the best solution approach (Drazin, 1990). Project team members need to coordinate and sometimes to negotiate to resolve these differences. To account for this limitation, this paper extends the existing VDT notion that treats actors as "engineering nerds" with complete goal congruence and models product developers as teleological professionals with potentially incongruent goals.

Because of the intricacy of modeling participants and work processes to predict organizational performance on semi-routine, fast-paced projects, we use a case-study approach (Eisenhardt, 1989b). In the following sections of the paper, we outline a semi-routine, fast-paced design project that we will later use for illustration of our representational model. We provide an overview of the engineering problem and the organizational challenges facing the case project manager. Section 3 discusses the conceptual building blocks necessary if our model is to meet these challenges. Section 4 reviews relevant organizational theories and presents the VDT framework on which we

---

[2] A "solution" is the unique end result of using a particular "solution approach" in a particular context. In routine and semi-routine work the result of using a solution approach has a clear and agreed upon, technical outcome. Since a particular solution approach always produces the same solution in a given context, we view the two as interchangeable. In comparison, non-routine work can be characterized by solution approaches that lead to ambiguous and potentially contested outcomes.

base our model, and concludes with a classification of our case modeling effort. Section 5 presents the representational extensions to the VDT framework necessitated by the modeling extensions. Section 6 links our representational constructs to behavior within an information-processing model of project teams and presents the results of a set of "virtual experiments" carried out on the model of the case study with the simulation framework. We conclude our paper with a summary of our practical and theoretical contributions, the limitations our model, and suggestions for future work.

2. The Norne Subsea Satellite Design Project—A Case Study

In this section, we give a brief description of the Norne engineering problem and the organizational challenges facing the Norne project manager to design an organization and work process that reduce costs by 30%.

2.1 Case Description

Our case study is taken from the Norwegian Offshore Oil and Gas industry and revolves around the process of pumping hydrocarbons from an oil and gas field using subsea satellites. This industry has faced a number of challenges in the past few years. First, the industry has moved away from exploration of larger oil fields in favor of smaller ones, precipitating a greater focus on reducing cost and time during development. In addition, the majority of new fields have been found farther to the north and in deeper water than existing oil fields. Traditional solutions and approaches for field development are impractical in these locations. The commonplace strategy of hooking gravity-based production platforms up at the seafloor is not feasible because of the water depth. Oil companies have attempted to develop new solutions by turning to new technologies and designs, of which subsea satellites are one example. Subsea satellites are structures located above the wells on the sea-floor designed to pump and transport oil or gas from the field to a floating or fixed platform or to inject water to maintain a high reservoir pressure and thereby improve oil and gas recovery. The main components of the Norne Subsea Production System are the following:

- A template structure that contains and supports up to four wellheads with piping and valves;

- A manifold module that performs subsea processing to prepare hydrocarbons for flow-line transportation;
- A "Xmas tree" structure that connects to the top of a well to control the fluid flow;
- Various connection tools that connect the Xmas tree with the satellite's pipes;
- A Blow-Out Preventer (BOP) to guard against unexpected gas and oil flow during drilling operations.

Developing an oil field using subsea satellites is a complex and challenging project. It involves a number of contracting companies in addition to the primary field developer. The initial stages of work are concerned with the conceptual and detailed design of the subsea satellite. Procurement follows, and the product is then assembled and constructed.

In June of 1994, Statoil, Inc., the Norwegian government-owned oil-company, began the Norne project to develop an oil field off the northern coast of Norway. Statoil granted the EPC (Engineering, Procurement, and Construction) contract for the subsea satellites to KOS (Kongsberg Offshore). The detailed design work for the subsea satellites was sub-contracted to Det Norske Veritas (DNV). This design project constituted around eleven thousand person-hours, carried out over eight months by an engineering design team of eleven engineers. Our case study focuses on the detailed design project.

Once the Norne subsea satellites are operational, it will be prohibitively expensive to perform repair or maintenance work on them due to difficulty of accessing them. Furthermore, environmental contamination is of great concern since any pollution is unacceptable. The Norne modules were thus designed to very high quality standards to ensure that they would operate reliably for extended periods without need for regular maintenance. At the same time, because Statoil mandated that schedules and costs for field development projects on the Norwegian continental shelf had to be reduced by at least 30%, the work schedule for the subsea satellites had to be shortened. As a result, nearly all activities had to be executed concurrently rather than in the traditional sequential manner (Figure 1).

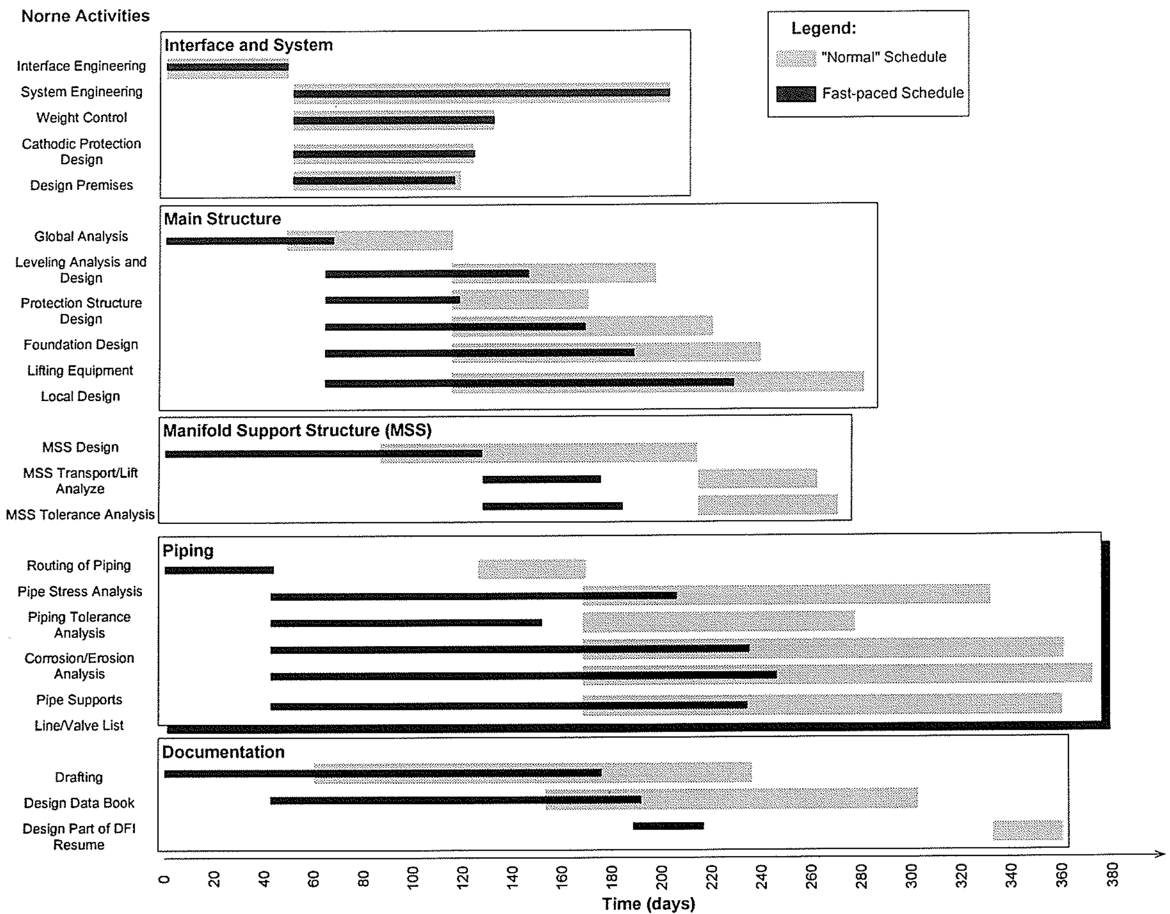

Figure 1: **The Norne Project Gantt Chart**. The thin dark bar represents the fast-paced Norne schedule, and the thicker, shaded bar overlaid on each thin bar represents a less fast-paced or more "normal" schedule for this type of project. The overall scope of work can be divided into four main blocks of activities. Activities in the Interface and System block take care of overall system issues as well as interfaces between the different main parts of the subsea template. The most important parts are the main structure, the manifold support structure, and the piping within the manifold. In addition, there is a portion of the work, which we call Documentation. This part consists of drafting and other design documentation. We focus our later discussion on the piping activities within the shadowed "Piping" block. Note the extremely high degree of concurrent execution of activities in the fast-paced schedule.

2.2 Organizational Challenges for the Norne Project Manager

The Norne project manager faced four main organizational challenges in achieving the tight goals mentioned above:

1. Most activities of the Norne project impose constraints on other activities. The resulting interdependencies between members of the project team require them to coordinate their work extensively during project execution, adding significantly to the time needed to complete each activity. However, not all activities are equally interdependent. Some actors need to communicate and coordinate more than others. The specific question was the following: *Where does interdependence most strongly* *affect the project, and where, in addition to the activities on the critical path, should I focus attention to meet cost, duration, and quality standards?*

2. The fast-paced nature of Norne requires professionals from multiple disciplines to collaborate intensely to develop solutions. The Norne professionals take pride in their craft and have their own perspectives on the best solution approach to meet the project goals. The specific question was the following: *Which professionals do I assign to activities to create a collaborative, innovative environment to meet the tight cost, duration, and quality standards?*
3. Even though project participants are professionals, they are not omniscient and omnipotent; they make errors. If an activity with an error is tightly linked to other activities, it is more likely that the effect of this error will be propagated and cause additional errors to related, concurrent activities. Thus, additional communication and coordination events will be generated. The specific question was the following: *How do I minimize the effects of errors on project cost, duration, quality?*
4. The client inputs to the detailed design phase was the contract and the specifications from conceptual design that break down the overall work into specified detailed requirements. Some requirements and some information were not completely available at the award of the contract. The fast-paced nature of the Norne project also led to frequent elaborations or adjustments of design requirements by the client. The specific question was the following: *How can I minimize the effects of uncontrollable client interventions, and at the same time meet overall cost, duration, and quality standards?*

Neither CPM, PERT nor DSM can give practical guidance to these questions. Thus, the Norne project manager had to rely on his own intuitions and experience to design an appropriate organization and project workflow. Based on a project manager's tangible knowledge of project requirements and activities, we will provide a quantitative methodology to derive key attributes of work processes and project participants. The resulting model is formal and executable so that a practitioner can run a set of exploratory simulations to predict organizational performance that are consistent, methodologically reproducible, and based on well-founded and widely accepted organization theory principles.

3. Conceptual Building Blocks

We saw in the previous section that the project manager's main concerns were (1) getting a measure of the level of interdependence between activities, (2) composing an efficient and effective project team, (3) minimizing error propagation, and (4) mitigating the effect of environmental uncertainty. In this section we present our conceptual building blocks that provide a starting point for our extensions to the VDT framework.

Following the prevailing view within traditional project management approaches (Kerzner, 1997), we consider a project as an open, autonomous unit embedded within a particular environment. However, rather than modeling the environment directly, we model instead the effects of the environment on the project. The environmental inputs to the detailed design phase are the contract and the specifications from conceptual design that break down the overall work into requirements and describe the overall conceptual solution to achieve them. The Norne project manager was able to relate requirements to project activities, and assign activities to different, specialized individuals or subgroups, i.e., actors. Typically, the actions undertaken to satisfy one requirement will affect the likelihood of accomplishing other requirements, and the actions required to satisfy multiple requirements simultaneously may conflict, i.e., activities' contributions to requirements may interact negatively (Hauser and Clausing, 1988). This leads to increased interdependencies between the specialized actors assigned to find acceptable solutions to accomplish particular requirements, and hence forces actors to coordinate intensely with each other.

The organizational contingency theorist, James D. Thompson (1967), referred to activities in which people are mutually and concurrently dependent on one another for information as reciprocally interdependent activities. We operationalize this form of interdependence between activities as *interdependence strength*. By representing interdependence in the form of strength, we are able to discriminate between activities' different pairs of interdependence relationships and only focus on those that are most important. Some of the Norne project activities contribute[3] to unique requirements, i.e.,

---

[3] An activity "contributes to" a requirement if the actions within the activity affect the accomplishment of the requirement.

they are independent, and the interdependence strength is zero. Other Norne project activities contribute to the same requirements, i.e., they are interdependent, and the interdependence strength is greater than zero. The participants responsible for interdependent activities must exchange information to find mutually satisfactory solutions.

To understand the resulting behavior of an actor working on a particular activity, we need to have some understanding of the lower level details of the activity that we have chosen not to include in our model. The actor responsible for an activity must have a behavioral repertoire available to meet the tightened performance targets (Weick, 1979). We want to capture how potentially different behaviors affect coordination and communication requirements. We have defined a characteristic of an activity as *flexibility* to account for alternative ways in which a particular activity may be carried out, without explicitly modeling each of the alternatives. Flexibility, then, is a measure of the size of the solution space that actors might consider when deciding how to execute an activity.

Actors have limited rationality (March and Simon, 1993). The more cognitive problem solving they have to perform, the more mistakes they make (Simon, 1997a). *Activity complexity* refers to how many variables must be considered simultaneously in one activity while solving a problem. The higher the activity complexity, the higher is the need for cognitive information processing and the higher is the probability of mistakes. We derive the complexity of a particular activity based on the number of requirements related to the activity and the difficulty in achieving each of the requirements.

Decisions about routine work can largely be made by applying routines and computation. In contrast, the flexible nature of fast-paced project work means that decision making requires *judgment* (Thompson and Tuden, 1959) and *interpretation* (Pava, 1983) by those professionals who carry it out. Professional actors from different occupational specialties have distinct perspectives on the best solution approaches (Mock and Morse, 1977). They assign different weights and rankings to the various criteria or project goals by which they evaluate each solution approach (judgment). Typically, these criteria include such factors as cost, duration, and quality. Based on their rankings, actors will exhibit a preference for one solution approach over others (interpretation). We refer to the difference in their ranking of criteria as *goal incongruency* between actors.

Incomplete client specifications at the beginning of the Norne project resulted in the subsequent release of a number of Interface Data Sheets (IDSs) during the course of the project. These documents include detailed requirements and information not completely available at the award of the contract. The number and the impact of IDSs can therefore be viewed *a posteriori* as representing environmental *uncertainty*. Separating factors that are controllable (related to work process breakdown and organization) from those that are not controllable (environmental uncertainty) will help focus attention on the area in which the project-team can have most influence in improving project outcome. This allows for both a more realistic simulation and one in which both controllable and uncontrollable outcomes are represented. In the organization contingency literature, uncertainty is treated as a qualitative variable describing the task environment faced by an organization as a whole (Duncan, 1972; Lawerence and Lorsch 1967). Since the client's change orders and refinement of specifications, as exemplified by the IDSs on the Norne project, affect particular activities in the project plan, we operationalize uncertainty at the activity level (rather than at the overall project level), and use this attribute to calculate coordination requirements between actors.

In summary, based on practical insights from the Norne fast-paced design project as well as organizational theory, we have identified five conceptual building blocks necessary for describing fast-paced design projects:

- Goal Incongruency between project participants;
- Activity flexibility;
- Activity complexity;
- Interdependence strength between activities;
- Activity uncertainty.

We will show in the remaining sections of this paper that these five conceptual building blocks provide the necessary representational foundation for addressing the project manager's four concerns: (1) getting a measure of the level of interdependence between activities, (2) composing an efficient and effective project team, (3) minimizing error propagation, and (4) mitigating the effect of environmental uncertainty.

The next section provides a review of our point of departure with respect to computational organizational modeling. This is followed by a detailed description of each concept and of how we derive values for conceptual building blocks for the Norne activities. Finally, we present a link between our conceptual building blocks and information processing in an organization.

4. Computational Organizational Modeling and Simulation

In this section, we discuss the appropriateness of a computational organizational simulation approach, our computational organizational modeling point of departure, and a classification of our modeling effort.

4.1 Application of Computational Organizational Simulation

Computational organizational simulation attempts to gain a deeper understanding of the effect of human behavior on organizational performance, and, ultimately, to develop tools for organizational managers (e.g., Carley and Prietula, 1994). A resurgence of interest in the field of computational organizational theory occurred in the late 1980's (e.g., Masuch and Lapotin, 1989). Combining new techniques in artificial intelligence with the information-processing power afforded by high-speed computers, researchers were able to use simulation to replicate the micro-level behavior of individuals to predict, inductively, the emergent, aggregate behavior of an organization. The simulation tools allow researchers to conduct a program of virtual experiments that would be infeasible using real-world organizations as subjects. Insights garnered from these virtual experiments can be used to answer a wide range of alternative "what-if" questions concerning the impact of various changes on organizational performance. These questions may pertain to changes in such areas as organizational structure, communication tools, the characteristics of personnel, and the structure or characteristics of the work processes.

However, before we can simulate a design project, we must define how the inputs of the simulation are derived from the real-world project plan and the organization. This representation should be explicit and declarative as well as rich enough to capture the characteristics of semi-routine, fast-paced design projects.

4.2 VDT—An Information-processing Framework for Simulation

Organizational contingency theory and the literature it has spawned on organizational design represent one of the most prominent theoretical approaches to understanding organizational performance (Pfeffer, 1996, p. 70). The organizational contingency perspective is founded on two chief precepts (Galbraith, 1973, p. 2). The first principle is that there is no one best way to organize. In other words, the suitability of an organization's structural arrangement is contingent on a number of factors called contingency factors. Contingency factors can, for example, be environmental complexity (Jurkovich, 1974; Tung, 1979) and environmental uncertainty (Duncan, 1972; Lawerence and Lorsch, 1967). Differences in structural configurations will be observed for different contingency factors (Donaldson, 1985). The second principle is that all ways of organizing are not equally effective. Specifically, organizations that demonstrate structures that fit the requirements of their environment will be more effective than organizations, which do not (Burton and Obel, 1995; Pfeffer, 1982, p.148).

Following Galbraith's (1973, 1977) information-processing view of contingency theory, researchers at Stanford University created the Virtual Design Team (Christiansen, 1993; Cohen 1992; Jin and Levitt, 1996). In the VDT simulation engine, organizations are conceptualized as a web of communication channels. Information is processed at the nodes or actors (i.e., project participants), and different types of communications (exceptions, decisions, information exchanges) are passed between the nodes through a variety of communication tools (e.g., email, fax, phone, etc.). In this way, the emergent behavior of an organization carrying out a particular work process can be simulated to assess organizational performance. A particular organization and work process will require more or less communication, leading to more or less primary work, coordination work and rework for actors, and ultimately to reliable predictions of project cost, schedule and process quality.

There are three principal representational components to a VDT model. First, there are actors, modeled as information-processing units, who perform tasks within the organization. There is only an abstract, statistical representation of the problem-solving or cognitive functioning of these actors—each actor has an in-box in which new tasks arrive, and a set of attention rules to determine which task to do next. Primary work, communication, and decision making all consume the actor's limited time/attention. A stochastic, object-oriented, discrete event-driven simulation engine controls tasks, performed by these actors.

Second, the interdependent actors are imbedded within an organizational hierarchy, which defines supervisor relationships and how exceptions to routine tasks are handled. The structure of this hierarchy defines the organizational framework in which the actors reside and the reporting and coordination structures that are present in the organization to resolve problems.

Finally, VDT has a rich representation of the work process within the organization. Activities are assigned to actors who are responsible for the successful completion of the tasks within those activities. Actors communicate with each other for two reasons. First, actors communicate in response to exceptions that are generated from processing tasks in activities. Second, actors exchange information about their processing of reciprocally interdependent tasks.

The VDT model is attractive because the process description holds a central place in the framework, and it is around these activities that the actors and their hierarchical reporting structures are framed. The project schedule becomes the process around which the work of the individuals within the organizations is executed and coordinated.

4.3 Classification of Modeling Effort

Types of product development work vary by industry. Firms in industries that place a strong emphasis on new product development, such as integrated microchip developers, will generally have a need for high work process flexibility to generate new innovative solutions. In contrast, in industries that produce mature products, the work process can be described as routine. For example, it is more important to a manufacturer of newsprint to ensure product reliability through preprogrammed routine work processes rather than to promote product innovation. To put our extended VDT model, called the Virtual Team Alliance (VTA), in context with other project management tools, we classify projects according to two important dimensions for project managers: "work process planning" (sequential vs. concurrent) and "work process routineness" (routine vs. non-routine).

The fast-paced schedule of the Norne activities led project activities to be executed in a highly concurrent manner. At the same time, activities were not preprogrammed, i.e., designers had flexibility to come up with their own solution approaches to tight performance targets. This flexibility led to a less routine work process, since there was more than one way to execute the activities (Thompson, 1967). Increased flexibility entails more communication and more exceptions. As the project becomes more and more concurrent, the impact of exceptions and the need for communication increases exponentially because of the high interdependence between concurrent activities.

In Figure 2, we show that CPM/PERT can be applied to sequential projects such as public construction works (roads, bridges, etc.). CPM/PERT may also be applied to fairly non-routine processes, such as development of new military equipment, using a stochastic scenario analysis approach. The VDT system has been applied in routine product development settings, for example in the design of a oil refinery (Cohen, 1992), in the Statfjord subsea satellite design for gravity-based production platforms (Christensen *et al.*, 1996), and in the design of power plants (Christensen *et al.*, 1997). In addition to the semi-routine, fast-paced Norne subsea satellite design, we have applied our VTA model to other industries such as the development of a commercial launch vehicle and a new generation of pyrovalves for positioning satellites in earth orbit (Thomsen *et al.,* 1998b; 1998c).

CPM/PERT, VDT and VTA are not suitable for contingent work processes, such as those found in engineering maintenance or health care delivery tasks. This is because diagnostic and repair tasks are by their nature conditional. Depending on the results of the diagnosis, different repair strategies will be used. To simulate the way an organization would perform these tasks, we would have to consider the conditional aspects of these tasks and not use the unconditional CPM/PERT model as a base for simulation of the work process.

Long-term basic research projects typically specify technical requirements, but how to achieve such requirements is often unknown. As a result, accurate work process estimates are difficult to make, historical data is of little value, and the schedule is often at the mercy of scientific discovery. Long term basic research, such as high-energy physics, is illustrated at the far right side of Figure 2. The development of AIDS drugs is the same kind of basic exploration, but AIDS drug development projects are much more fast-paced because of social needs. None of these endeavors is suitable for analysis in CPM/PERT, VDT or our VTA model.

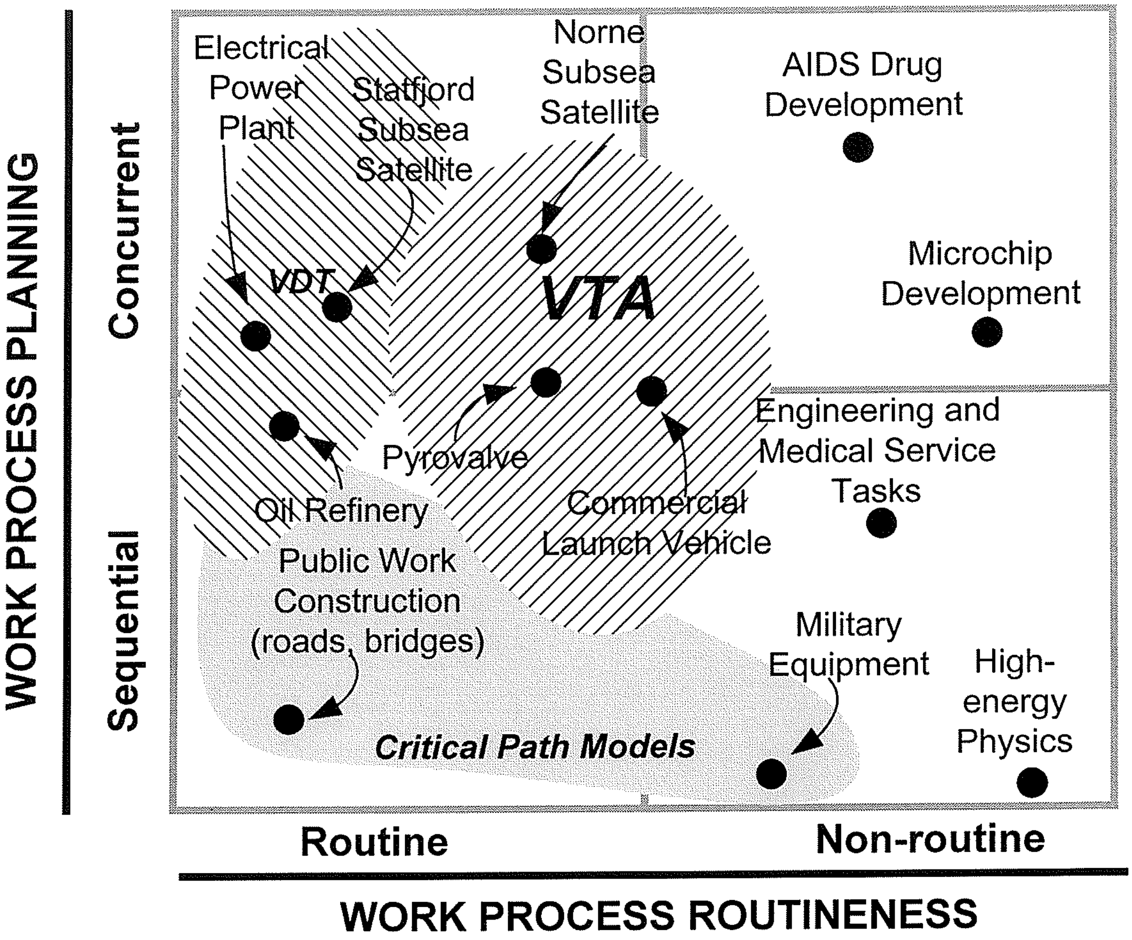

Figure 2: **A Qualitative Comparison between CPM/PERT, VDT, and our VTA Model.** It shows the "organizational space" of applicability of different project management tools (bubbles).

5. Representation for Semi-routine, Fast-paced Design Projects

The Virtual Design Team is our point of departure for the representation of semi-routine, fast-paced design projects. An information-processing view of the design project such as that used in VDT focuses attention on the work process and the way in which communication and coordination requirements affect these work processes and *vice versa*. Extensions to this framework allow us to go beyond a paradigm that (1) treats the project professionals as being goal congruent and (2) assumes idealized, routine work processes. We have made extensions to the traditional "information-processing" view of the actors to accommodate the different perspectives that might exist in teams of diverse professionals (goal incongruency), and we use a richer representation for work processes (activity complexity, uncertainty, flexibility, and interdependence strength). These extensions allow us to represent how exceptions or unexpected events arise in semi-routine, fast-paced projects and affect the work process. In the following sections, we describe these modifications to the VDT actor and the work process representation that allow us to represent a semi-routine, fast-paced design project more realistically.

5.1 Modeling Project Participants

The Norne subsea satellite project included highly skilled managers, structural engineers, piping engineers, geo-technical engineers, material experts, drafting technicians as well as other professionals. Each of these professions has a unique perspective on alternative solution approaches to design problems. In deciding on the best solution approach for multiple and possible conflicting requirements during the course of the project, each member of the project team contributed his or her perspective, at times with conflicts that needed to be constructively resolved by collaboration or hierarchical decision making.

Differences in opinion occurred not only between team members in the problem-solving process, but also between team members and their supervisors. The explicit or implicit goal ranking of the supervisors, encoded within assigned work packages, may be different from those of the actors working on finding solutions to the work packages. These differences affect the level of compliance with the project plan recommendations. Deviations from the original project plan may give rise to more coordination and communication between members of the project team and therefore lengthen the total project duration and increase cost.

In introducing actor goals to our model, however, we wish to avoid the complexity of decision-theoretic or utility-based representations (Howard and Matheson, 1983). Our approach is more descriptive than normative—we are interested in behavioral changes within the organization in response to goal incongruency between actors, not in the actual approach that will be used in problem solving. We extend the simple VDT actor notion that assumes that actors have only abilities (skills and experience). We model actors as "teleological" (i.e., goal-directed) knowledgeable agents. *While an actor's ability* *determines the quality of actions carried out, an actor's prioritizing of goals suggests which actions will most likely be carried out.*

We operationalize these different perspectives as goal incongruency between project participants and follow the "benevolent agent assumption" that Rosenschein and Genesereth (1985) described. They assume that goal incongruency between actors arises because of differences in their perspectives or in their beliefs concerning how to best serve the interests of the organization. The project management literature (e.g., Kerzner, 1997) posits cost, duration, and quality as the chief project goals. An actor's best way to serve the project is therefore to focus on the overarching goals of cost, duration, and quality rather than on personal goals. This perspective is at odds with the view in utilitarian economics that professionals engage in rational calculus for maximal self-interest (Bonner, 1995), but has widespread support in the literature on professions that suppresses the assumption of self-interest in favor of greater emphasis on altruism[4] (Chiles and McMackin, 1996; Ghoshal and Moran, 1996; Nass, 1986). It is also consistent with the assumption of boundedly rational actors (Simon, 1997b).

Cost, duration, and quality are reciprocal constraints, since maximizing one tends to diminish one or both of the other variables. Because of professionals' local expertise and social position in the institutional infrastructure of their respective "communities," they will most likely prioritize these goals differently. As a result, their aspirations for

---

[4] We believe that our model of goal incongruency and its effects on behavior can be extended to model differences in goals that arise due to self-serving behavior and asymmetric information in principal-agent transactions. Principal-agent goal incongruency can be viewed as a difference in emphasis on specific kinds of costs and benefits associated with alternative solution approaches available to the agent. The agency literature (e.g., Eisenhardt, 1989a) posits that the principal-agent problem arises from goal and information asymmetry. In a given transaction, the agent favors solution alternatives that minimize its costs, whereas the principal favors alternatives that maximize its value; since the principal cannot monitor all areas of the agent's behavior, the agent may shirk. Principals respond to this conflict in goals by attempting to give incentive to the agent to emphasize the principal's goals along those behavior or outcome dimensions that can be monitored by the principal at the lowest cost. We plan to apply the VTA framework to principal-agent transactions that arise when project managers subcontract with external vendors for the design and manufacturing of components as an extension of this research.

solution approaches may differ significantly enough that actor decision-making and project performance will be affected.

The extent to which professionals need to make trade-offs among project goals, however, is contingent on the level of slack within the organization (Cyert and March, 1992). Following Simon's (1997b) "satisficing" view of organizational decision-making, all goals, given enough slack, can be achieved at a satisfactory level of performance so that no trade-offs are necessary. The challenging technical requirements and fast-paced nature of the Norne project ensured that slack was at a minimum level. For such a project, goal incongruency clearly matters, since it affects the different professionals' choices of solution approaches with varying trade-offs among time, cost and quality goals.

We developed a methodology for gathering data on goal incongruency within the Norne project team based on Chatman's (1991) card-sort method. We asked the project manager to list the most important project goals. Each project participant was asked to sort a card-set of these project goals in order of his or her priority. We calculated the distance in goal priorities between project participants by simply summing up the absolute differences in the ranking of each goal (Figure 3). We asked the project participants to

1. Rank order the importance of "completing tasks on time (D)," "staying within budget (C)," "striving for high task quality (Q)," "focusing on safety in solutions (S)," "pursuing self-improvement (SI)," and "minimizing risk of project failure (R)," with the possibility to indicate equals;
2. Indicate whether the relative importance of the first and second is "first equal to second (=)," "first somewhat more than second (≥)," or "first more than second (>)" or "first much more than second (>>);"
3. Repeat for second, third, fourth, and fifth choices.

The Norne project participants felt most comfortable only using (>) to discriminate among the rank ordered items. Table 1 shows the result of the Piping Leader and Project Manager's ranking.

	Rank Piping Leader	Rank Project Manager	Rank |difference|
D	2	1	|2 - 1| = 1
C	5	5	|5 - 5| = 0
Q	3	4	|3 - 4| = 1
S	1	2	|1 - 2| = 1
SI	6	6	|6 - 6| = 0
R	4	3	|4 - 3| = 1
			Sum: 4

Table 1: **Goal Incongruency between the Piping Leader and the Project Manager.** The resulting goal incongruency between the Project Manager and the Piping Leader is four.

In general, higher-level actors focused on duration, whereas lower-level actors put more emphasis on quality. When specifically asked the lower-level actors focused on the dimensions of quality most pertinent to their discipline, as the literature on professions predicts. There is a debate in the social science literature (e.g., Osgood *et al.*, 1957) about whether dissimilarity indices should be based on comparative judgments or subtraction of absolute values. We decided to use subtraction of absolute values for our retrospective Norne case study. We collected goal incongruency data about a year after the completion of the Norne project, and by then some of the Norne project participants no longer had a vivid enough recollection to make comparative judgments about their perceptions of other Norne project participants' goals.

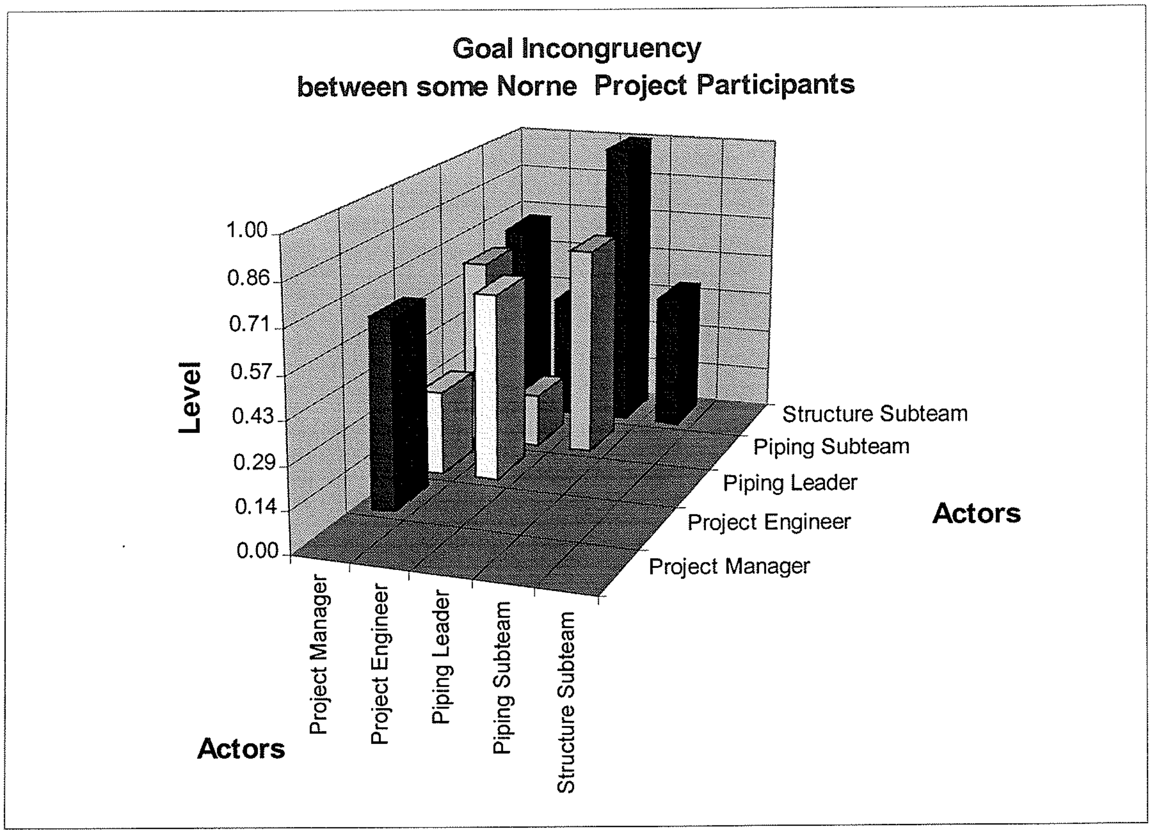

Figure 3: **The Level of Goal Incongruency between Different Groups within the Norne Project**. The values have been normalized, so that the actors with the highest incongruency have a value of 1.0. We see, for example, that the goal incongruency between the Project Manager and the Project Engineer is much higher (0.6) than between the Project Manager and the Piping Leader (0.3).

Our representation of goal incongruency extends the VDT actor view by modeling project participants as professional designers with novel perspectives. Using our goal incongruency instrument the project manager can realistically capture actors' different perspectives. The project manager can compose a project team with an appropriate level of goal incongruency to foster a collaborative innovative problem-solving environment so that tight cost, duration, and quality goals are met (section 2.2, challenge 2).

5.2 Modeling the Work Process

Similar to the Virtual Design Team representational framework, our VTA framework includes measures of activity work volume and required skills, but modifies the measures of complexity and uncertainty and adds representations for activity flexibility and interdependence strength to reflect the particular characteristics of these less routine, fast-paced facility design projects.

5.2.1. Activity Flexibility

Activity flexibility reflects the number of ways in which a particular activity within an organization can be done. Activity flexibility is either derived from a product model (Willems, 1988), from a description of activities within the organization (e.g., Malone *et al.*, 1993), or directly from estimates of domain experts. Values for each of the Norne activities were estimated by domain experts using a Likert scale from 1 to 9, but could have been derived from product models if the product model had indicated the number of potential solution approaches instead of only the actual solution approach. For example, piping experts may consider that calculations by hand, heuristic arguments, linear Finite Element Analysis (FEA), nonlinear FEA, and fatigue analysis are alternative solution approaches to the Pipe Stress Analysis activity. The Norne Piping Leader estimated the "Pipe Stress Analysis" flexibility, f_2, to be five. For the "Pipe Supports" activity the piping experts have to consider different pipe support solution approaches such as round bar pipe clamp u-bolts, square u-bolts, flat bar pipe clamp overstraps, clamp holder angle bars, pads, and hydraulic clamps of polypropylene or polyamyd. The Norne Piping Leader estimated the "Pipe Supports" flexibility, f_5, to be six.

Figure 4 shows the values for activity flexibility (and activity complexity and uncertainty that we discuss later) derived from expert opinion for each of the activities for the piping design. The values have been normalized to simplify the translation to the symbolic values high, medium, or low. The bar on the right indicates relative values of high, medium, and low flexibility that we use in computer simulations with the VTA system. In this example, we have used a linear method to assign the values high, medium, and low to partitions. In other circumstances, a logarithmic or other method might be more appropriate to create a spectrum of input values and provide better differentiation among activity values.

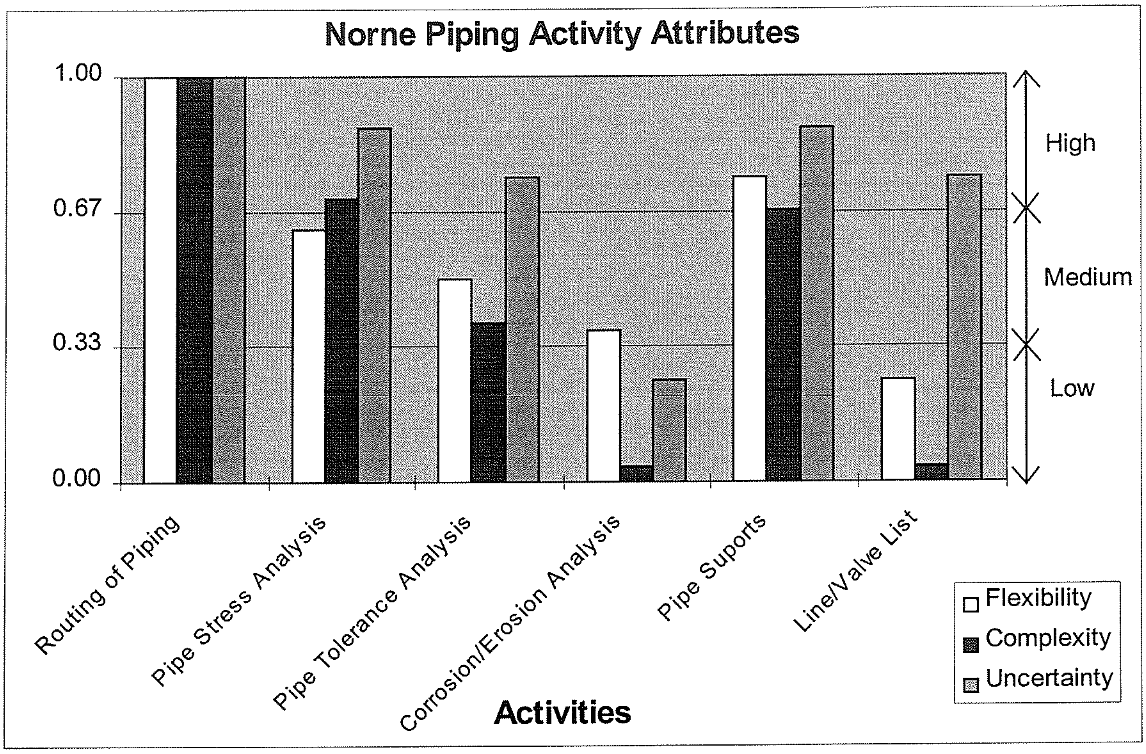

Figure 4: **Activity Flexibility, Complexity, and Uncertainty for the Piping Design Activities.** The activities with the highest flexibility, complexity, or uncertainty have a value of 1.0. We then translated the normalized values to symbolic ordinal values high, medium, or low.

Our representation of activity flexibility as an indication of the number of potential alternatives for executing an activity provides a measure for activities in which creating and applying knowledge is an important element. The success of collaborative problem solving in the face of activity flexibility depends on the project manager's activity assignment of actors with an appropriate level of goal incongruency as well as level of skill (section 2.2, challenge 1 and 2).

5.2.2 Requirement Complexity and Activity Complexity

The complexity of an activity is a measure of the cognitive problem-solving load that a particular activity will impose on the actors within the organization. We derive the complexity of a particular activity from the various requirements to which the activity contributes. In light of our objective of analyzing and predicting behavior of individual actors, we do not represent overall abstract project requirements but only lower level requirements which, as research has shown, drive the behavior of individual project participants (Locke and Latham, 1990). The project objective can be iteratively decomposed into detailed requirements pertaining to each component of the system (Willems, 1988). However, Willems' functional unit/technical solution hierarchical decomposition approach was too cumbersome for capturing the sheer number, i.e., 128, of requirements of the Norne project. Fortunately, the Norne requirements could be easily extracted from the plan and domain experts, along with other information such as the contract documents. Activities that contribute to many different (possibly conflicting) requirements will require more "cognitive energy" than simple activities that only relate to one or two requirements. For example, the "Route Piping" activity not only routes the pipes, but aids in controlling the weight of the template as well as the design of the manifold support system. Then the cognitive problem solving has high complexity since designers must take into account all these requirements when deciding routing.

Moreover, activity complexity depends not only on the sheer number of requirements but also on the difficulty of satisfying each individual requirement (i.e., requirement complexity). For example, "Resist External Environment" (Corrosion) is a fairly simple requirement. There exists one standard way of performing the calculations to determine the surface area of the subsea satellite which is used as input to determine how many anodes are necessary to keep corrosion within acceptable limits. A much more difficult requirement is to find a satisfactory level of piping stiffness. To satisfy this requirement, the designer must consider a trade-off between stiffness and strength when finding a solution approach. In searching for a satisfactory solution approach, the designer also has to consider that connection tools for the alignment of the Xmas tree affect the level of piping stiffness necessary. In short, there are many potential solution approaches (as measured by activity flexibility) to consider, some more effective than others. Therefore, we derive the complexity of an activity based on the number of requirement that must be considered in choosing an alternative and on the difficulty in achieving each of the requirements.

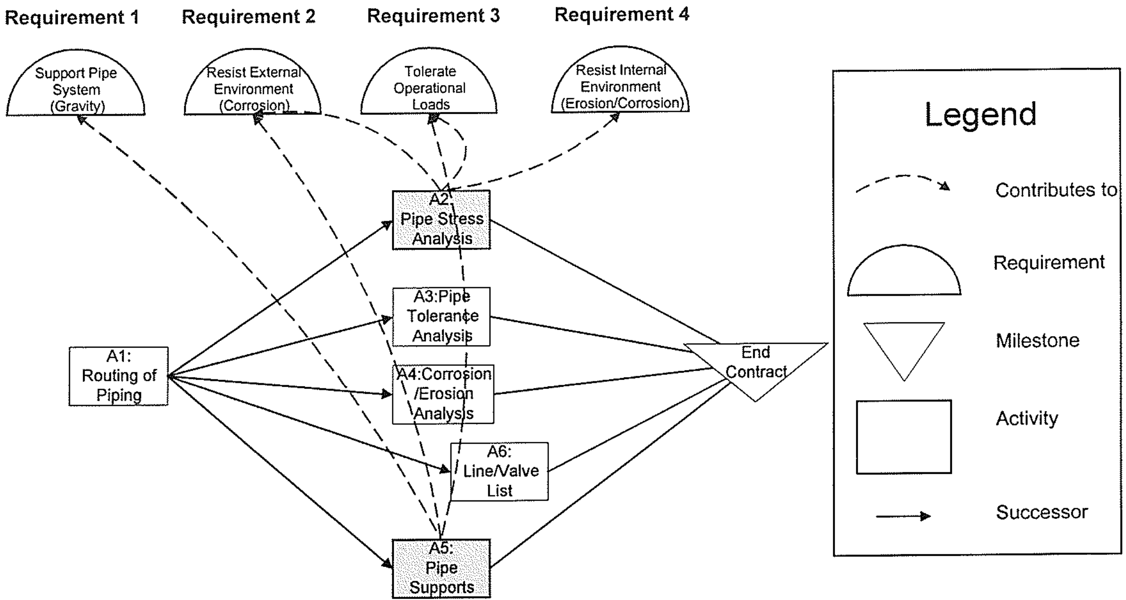

Figure 5: **Linking Activities to Requirements.** A portion of the project plan for the Norne Subsea Satellite Design showing the requirements for two activities within the piping part—"Pipe Stress Analysis" and "Pipe Supports." Requirement 1—"Support Pipe System" (Gravity) is solved by the weight evaluations of the pipes, valves, and hubs in the "Pipe Supports" activity. Requirement 2—"Resist External Environment" (Corrosion) includes such issues as currents and corrosion. The force from currents is transmitted through the pipes to the pipe supports. External corrosion due to seawater has to be considered both for the "Pipe Stress Analysis" and "Pipe Supports". Requirement 3—"Tolerate Operational Loads" includes such considerations as pressures and temperature expansions that both the "Pipe Stress Analysis" and the "Pipe Support" have to consider. Requirement 4—"Resist Internal Environment" (Erosion/Corrosion) includes such issues as erosion due to sand and corrosion due to sulfurous gas and oil that affect only the "Pipe Stress Analysis" activity.

Figure 5 illustrates how activity complexity is determined for a subset of activities for the piping part of the project plan. The diagram has been simplified to show the interaction between only two different activities—"Pipe Stress Analysis" that depends on the pipe arrangement, and "Pipe Supports" that includes the design of supports for the pipes, valves, and hubs (connection parts between pipes and external pipelines). These activities contribute to four requirements—two are shared, and two are unique to each of the activities.

First, we determine requirement complexities. Requirements that are impacted by many different activities are more complex than those that require a single activity to be successful. Cognitively, actors consider more factors in solving those requirements since they consider the solution approaches in each of the activities together to determine a satisfactory solution approach to use. Those requirements that are met by only a single activity need only to consider the solution approaches for that activity in determining the cognitive load of the an actor. We claim that requirement complexity increases linearly, or combinatorically, as a function of the number of potential solution approaches in activities that contribute to the requirement. If activities' contributions to requirements interact negatively, the total number of potential solution approaches is not the sum of solution approaches in each individual activity, but any combination of solution approaches in those activities that contribute to the requirements. To determine activity complexity, we add the requirement complexities of each of the requirements to which the activity contributes. We argue that activity complexity increases as a linear function, not exponential or factorial function, of requirement complexity. An actor responsible for an activity considers one requirement at a time (March and Simon, 1993). Each potential solution approach to that requirement either satisfices or does not satisfice the actor's project goals (in terms of their aspiration levels and relative priority). Following March and Simon, we assert that the actor's aspiration level determines the satisficing stop rule (Simon, 1956). If a solution approach cannot be found that satisfices, the actor's aspiration levels will drop until a satisficing solution approach is found (Soelberg, 1967; Simon, 1997b, pp. 323-324). In our example above, the complexity of requirement 1 is equal to the number of alternative solution approaches for activity A_5, i.e., f_5. The complexity of requirement 2 and requirement 3 is the sum of the alternative solution approaches for A_2 and A_5, $f_2 + f_5$. Our collaborating project manager maintained that the contributions of activity A_2 and A_5 to requirement 2 and requirement 3 did not interact negatively. Thus, for A_5 the complexity is determined as follows:

$$\text{Complexity}_{\text{A5}} = \sum_i \mathit{Complexity}_{R_i}\ ,\ \forall \text{ requirements } (R_i) \text{ of } A_5$$

$$= \text{Complexity}_{\text{R1}} + \text{Complexity}_{\text{R2}} + \text{Complexity}_{\text{R3}}$$

$$= f_5 + (f_2 + f_5) + (f_2 + f_5) = 2f_2 + 3f_5 = 10 + 18 = 28 \qquad (1)$$

Figure 4 shows the normalized activity complexities derived for the piping activities.

Actors make errors. The higher the activity complexity level, the higher the predicted error rates. Using our activity complexity representation, the project manager can focus his/her attention on the activities with the highest probability for errors (section 2.2, challenge 3).

5.2.3 Interdependence Strength

In subsea satellite design tasks, structural engineers, piping engineers, materials experts, geo-technical engineers, draft technicians and other professionals gather and exchange information to make appropriate design decisions, and then perform their activities based on those decisions. This problem-solving approach requires a significant amount of coordination and communication—design information must be relayed from the structural designers to the material experts or geo-technical engineers, and the drafting technicians' response to design decisions must be monitored. For example, the structural engineers estimate the necessary size and weight of the template structure based on customer requirements. The geo-technical engineer combines these data with soil data and suggests a satisfying foundation solution. After several iterations, when the structural engineers and the geo-technical engineers have found a mutually satisfying solution, the drafting technicians complete the design drawings. If the number of valid alternatives that must be considered in performing an activity increases, it can become progressively more difficult to choose among alternatives. Moreover, for interdependent activities, the adoption of one particular alternative can have significant consequences for other activities. Therefore, actors must communicate more with each other to derive a mutually satisfactory solution that will fulfill the requirements for all interdependent activities.

Quality Function Deployment (QFD) maps interrelationships between requirements and solutions (Hauser and Clausing, 1988). QFD is useful for deriving the activities that are necessary to meet customer expectations. In our framework, however, we take the project activities as given. If the Norne project manager had performed a prior QFD analysis, it would have helped everyone involved to identify which activities contribute to which requirements and the sign of the activity interactions (positive or negative). However, even if he had not performed a QFD analysis, he could still easily map activities to requirements derived from the contract and other information from the conceptual design. All activities that share requirements are considered interdependent. Shared requirements require that different actors (1) use their local expertise and information to formulate partial solutions and (2) integrate their solutions with those of other actors to build an overall solution that provides the best overall tradeoff among project goals. For example, pipe routing determines where to place the pipe supports on the manifold support structure, and the pipe stress analysis determines whether the routing and support are sufficient to meet the operational loads. The responsible actors for these activities have to communicate intensively to find satisfactory solution approaches that meet the requirements of all the respective activities.

In a similar way to activity complexity, we can calculate interdependence strength between activities as the sum of the strengths (i.e., requirement complexity) of the individual links (i.e., requirements) connecting activities. In our example, illustrated in Figure 5, A_2 has two links (i.e., two common requirements) to A_5, so the interdependence strength is calculated as follows:

$$\text{InterdependenceStrength}_{A2A5} =$$

$$\sum_i \mathit{Complexity}_{Ri}\,,\ \forall \text{ shared requirements } (R_i) \text{ of } A_2 \text{ and } A_5$$

$$= \text{Complexity}_{R2} + \text{Complexity}_{R3} = (f_2 + f_5) + (f_2 + f_5) \;= 2(5+6) = 22 \qquad (2)$$

Our representation of interdependence strength between activities operationalizes the notion of interdependence and captures that, given a set of activities and related requirements, some actors need to communicate and coordinate more than others, and that errors will propagate between interdependent activities (e.g., when shared requirements are not met). Figure 6 shows the normalized interdependence strength for activity-activity relationships within the piping activities.

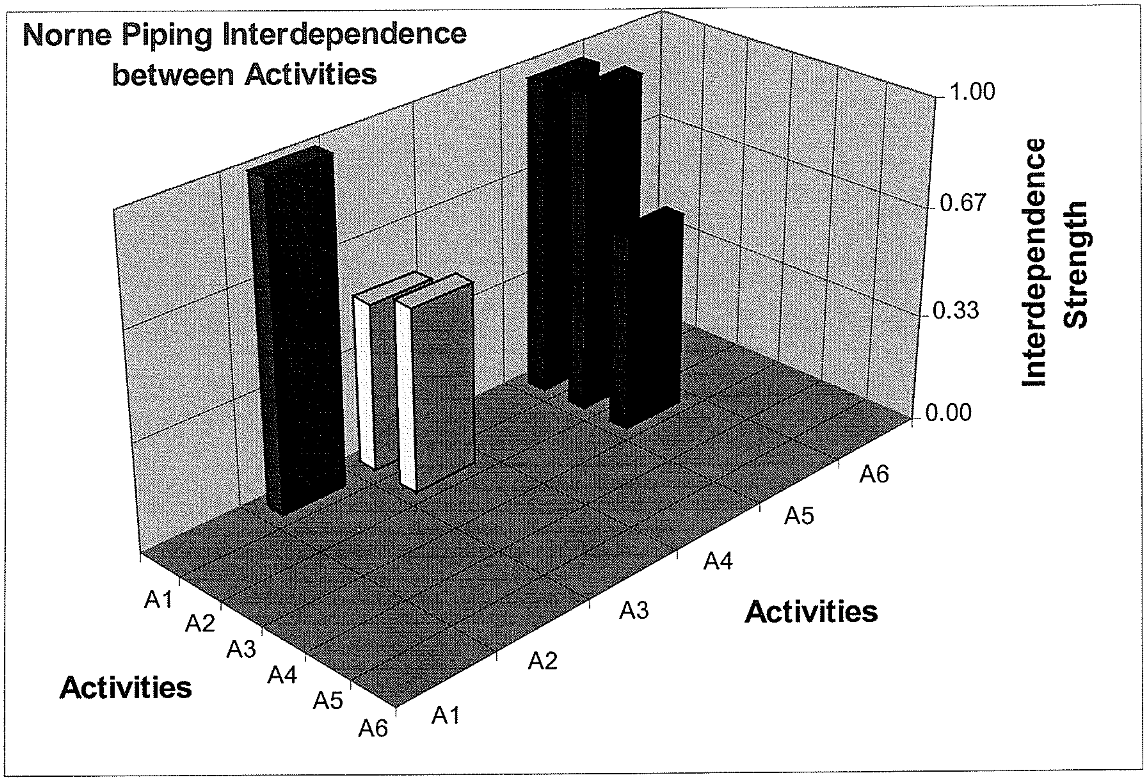

Figure 6: **The Interdependence Strength between Activities.** The 3-D graph shows the interdependence strength between each pair of activities. Routing of Piping (A1) and Pipe Stress Analysis (A2) are most interdependent, whereas Erosion/Corrosion Analysis (A4) and Line/Valve List (A6) are least interdependent with other activities.

By using our representation, project managers get information on where activity interdependence is most likely to affect the project, and where, in addition to the activities on the critical path, they should focus attention (section 2.2, challenge 1 and 3).

5.2.4 Matrix Representation

For the Norne project, we derived 128 requirements from interviews with the project manger as well as input documentation to detailed design. 23 activities contributed to these 128 requirements. If we have many activities and many requirements, matrix representation can more easily accommodate these calculations. For example, if we have n activities in a project plan that contributes to m requirements, the activity complexities as well as the interdependence strengths between activities can be determined from the matrix $\mathbf{H}$.

$$\mathbf{H} = \mathbf{R}^T(\mathbf{RFR}^T * \mathbf{I})\mathbf{R} \tag{3}$$

where

R is a m by n matrix of requirements and activities. In each of the cells in which a requirement and an activity intersect, a value of one indicates that the activity contributes towards satisfying that requirement. Otherwise, the default value of 0 indicates no relationship between the activity and the requirement.

$\mathbf{R}^{\mathbf{T}}$ is the transposed matrix of **R**.

I is a m by m identity matrix.

F is a n by n diagonal matrix with activities located on the rows and columns. The activity flexibility is represented in the diagonal.

H is a symmetric n by n result matrix. The resulting diagonal elements of the matrix give the activity complexity for each activity, and the off-diagonal elements give the pair-wise interdependence strengths.

The * operator indicates a point-wise multiplication of the elements in two matrices, in a process called "congruent matrix multiplication" (Howard, 1971, pp. 549-550).

For example, in our simple case with four goals and two activities discussed above,

$$\mathbf{F} = \begin{bmatrix} f_2 & 0 \\ 0 & f_5 \end{bmatrix}, \mathbf{R} = \begin{bmatrix} 0 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 0 \end{bmatrix}. \text{ Eq. (1) gives } \mathbf{H} = \begin{bmatrix} 3f_2 + 2f_5 & 2f_2 + 2f_5 \\ 2f_2 + 2f_5 & 2f_2 + 3f_5 \end{bmatrix} \text{ as expected.}$$

5.2.5 Activity Uncertainty

Activity flexibility, complexity, and interdependence strength are derived based on knowledge about project requirements at the beginning of a project. Inherent uncertainty in design technology is captured in our activity flexibility concepts. However, in fast-paced design projects, the environment, e.g., the customer, continuously refines requirements during the course of the project. Activity uncertainty results in more communication between interdependent activities. In the Norne project, this was handled through Interface Data Sheets (IDSs) that documented changes to initial specifications and elaborated on performance requirements. In total, there were about 30 IDSs during the Norne Design Project that required from one hour to one week of extra work. For example, the Protection Structure Design was based on some initial geometric specifications about the weight and geometry of the BOP (Blow-Out Preventer).

However, as the design project progressed, these initial specifications changed because of decisions about which specific BOP to use.

The IDSs serve as a good measure of activity uncertainty after the fact. However, since the IDSs are typically not available at the start of projects, we derive activity uncertainty directly from estimates of domain experts. Values for each of the Norne activities were estimated by domain experts using a Likert scale from 1 to 9 (Figure 4). Some activities are more prone to uncontrollable client interventions than others. Our activity uncertainty representation helps the project manager model and simulate an organization to design a work process and organization that maximizes robustness against the effects of uncontrollable client interventions and meets overall cost, duration, and quality standards (section 2.2, challenge 4).

6. Linking Representation to Behavior

The extensions to the VDT representation described above show how we link real-world observation to attributes that represent fast-paced projects in a computer model. Now, we must link our representation to the behavior that we wish to observe in our simulation. We are interested in the effects of actor ability, goals, as well as activity flexibility, complexity, uncertainty, and interdependence strength, have on the communication and exception handling required for a particular organization to complete a particular work process. Since the behaviors in VDT affect how well an organization is able to meet duration, cost, and quality goals, we must tie our representational constructs to communication behavior that occurs within VDT. There are two communication processes modeled and simulated in the VDT (exception generation and information exchange), and two kinds of decision making are explicitly modeled (attention allocation and whether or not to do rework when an exception is detected).

6.1 Exception Generation

"Information exceptions" are unexpected events that occur during the process of design, which overwhelm the cognitive capacity of the responsible team member. They are resolved through vertical communication (subordinate-supervisor or subordinate-functional manager) channels in the project organization. Any time that the information available is less than the necessary information, an information exception may be generated after each task (Galbraith, 1977). We introduce an additional kind of "decision-making" exception. Decision-making exceptions occur probabilistically when an actor makes a decision about an engineering process that deviates from the usual process. In response to exceptions, pre-planned tasks may be modified or replaced. The number of exceptions that arise is affected both by the skill and goal priorities of the actor responsible for the activity and by the routineness of the activity. Fast-paced schedules, in turn, increase the impact of exceptions, and therefore the coordination and rework load, dramatically.

Determining how to improve the project plan or the organization requires knowledge about the kinds of exceptions that may arise. VDT models only two types of exceptions: internal exceptions and external exceptions, both of which may require rework. Thus exceptions can only affect performance negatively. In our VTA model, we distinguish between two different kinds of exceptions, technical errors (information exceptions) and non-conformances (decision-making exceptions), each of which has a different effect on the organization and its actors. Technical errors are always nonproductive. However, unlike technical errors, non-conformances are not necessarily undesirable.

6.1.1 Technical Errors

Errors of judgment (technical oversight) and errors of skill (technical incompetence or lack of diligence) are both considered technical errors. The probability that an activity will have a technical error is related to activity complexity as well as the match between skill requirements of the activity and the skill of the responsible actor. A combination of complex activities with less able actors is likely to result in more technical errors than a combination of simple activities and able actors. Technical errors are always detrimental to the product quality or successful completion of the desired objective, and they must be corrected to ensure the reliability and functionality of the product. Technical errors in one activity will, based on interdependent strength, stochastically generate technical errors in any interdependent activities.

The technical error is forwarded to the appropriate supervisor, depending on the level of centralization of decision making, who decides whether to repeat the portion of the activity that generated the error, to "quick-fix", or to ignore the error. Quick-fixing or reworking an error takes more time than ignoring the error. For example, the Norne project formalized the handling of technical errors through an Engineering Change Sheet (ECS). Any technical error in the original plan was documented on an ECS and forwarded to the appropriate decision-maker. The decision-maker informed other actors who might be affected by the error. The complexity of the activities or the way in which the project plan is organized can lead to technical errors and communications. These additional communications will have a significant effect on the productivity and effectiveness of the project team in performing the project plan.

We conducted a simple validation experiment on the Norne model using the VTA simulation to triangulate the model against the predictions from qualitative organizational theory and estimates from the Norne project manager. We used the actual input model as a reference-point and changed all actor-activity skill matches to low (BS, and less than three years of relevant task experience), medium (MS, and between 3 and 6 years of relevant task experience) and high (MS or PHD, and more than 6 years of relevant task experience). Organizational contingency theory predicts that the better the fit between the actor's skill and the skill requirements of the activity, the shorter the activity duration (Christiansen, 1993). The Norne project manager's predictions were in accordance with theory, but more pronounced for a higher level of actor-activity skill match. Figure 7 shows these relationships. Simulation results were stable and agreed qualitatively with organizational contingency theory[5].

---

[5] To determine whether the simulation results were consistent with the manager's predictions, we performed t-tests, which treated manager's predictions as an estimate with a standard error of 5%; we used computed standard errors for the statistical simulation. The t-statistic was computed for high, medium, and low levels of actor-activity skill match. In all cases, the t-statistic was extremely small (maximum $t=1.1$), suggesting that the simulations were consistent with the manager's predictions. It should be noted that the simulation results were stable, with a coefficient of variation (CV) between 3 and 6 percent for all settings.

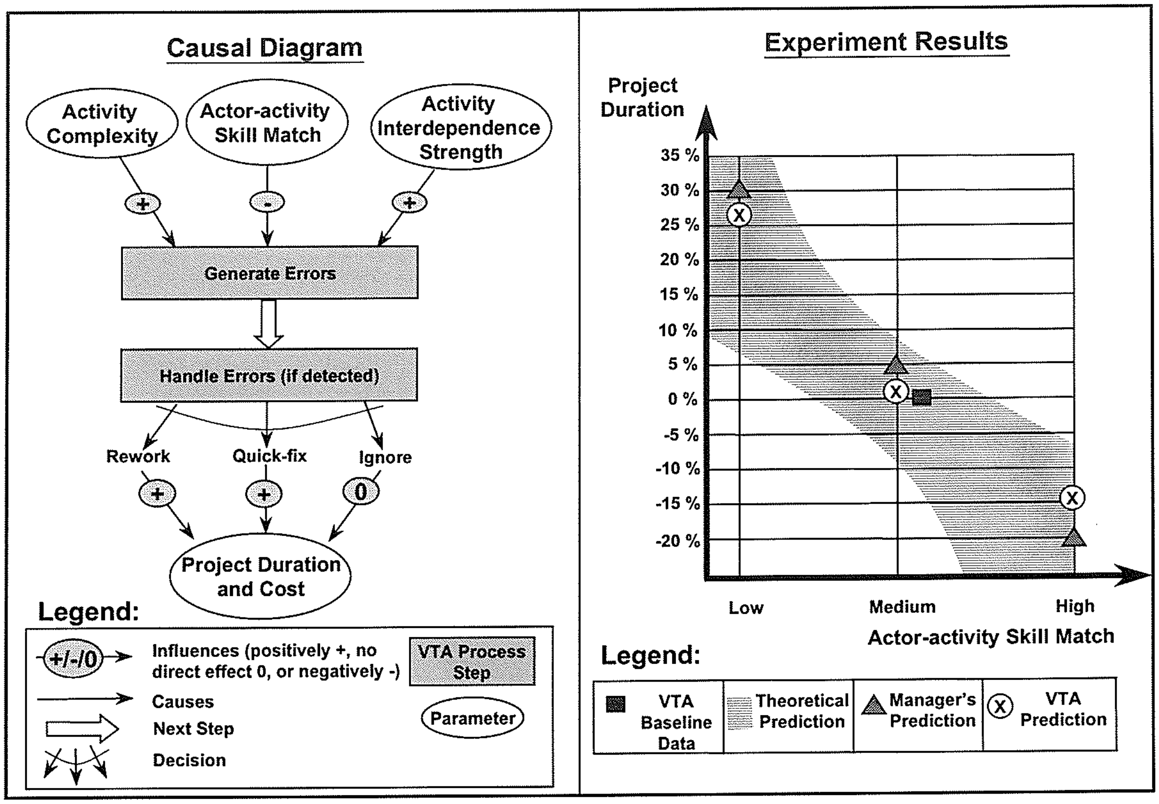

Figure 7: **The Effect of Activity Complexity, Actor-activity Skill Match, and Interdependence Strength on Project Performance.** The activity complexity and actor-activity skill match determine the likelihood for a technical error to occur. Activity interdependence determines whether the technical error will be propagated to other interdependent activities. The right part of the figure shows the results from our simulation analysis. The Norne project had a reasonable close actor-activity skill match, but the simulation results predicted that an even better match would have reduced project duration by about 15%.

6.1.2 Non-conformances

The second type of exception is a non-conformance (NC). In this case, the actor responsible for completing the activity has not made mistakes. He has chosen to use another method to achieve the requirements of the activity than the one anticipated by the manager of the project plan (i.e., the final design product will not necessarily be defective if the NC is not remediated). For example, in the Norne project, the manager expected to use square skirts as the solution for the foundation. However, the foundation engineers selected circular skirts instead to reduce the amount of stiffening (i.e., weight and cost) required to absorb the internal over-pressure in skirt compartments. Foundation design activity flexibility combined with the foundation designers' different perspective on the problem solving allowed for solution creativity and improvement.

The factors that affect an NC exception are different from those that cause a technical error. In NCs, it is activity flexibility, and the difference in ranking of goals, i.e., goal incongruency, between the responsible actor and supervisor that affects whether a NC is likely to occur. Activities with a high degree of flexibility and actors with goal priorities very different from the supervisor's (i.e., high goal incongruency) will tend to have a high number of NCs. In turn, the relative skills of the supervisor and the subordinate influence the effect this NC will have on project cost and duration (productive or nonproductive). For example, a relatively unskilled supervisor will encounter more productive NCs from a highly skilled subordinate than *vice versa*. The decision-maker determines whether to accept, modify, or reject the NC. Its decision affects the project cost and duration (Figure 8).

As with technical errors, we conducted a simple validation experiment on the Norne project using the VTA simulation engine to triangulate our model against the predictions from qualitative organizational theory and predictions from the Norne project manager (Figure 8). We used the actual input model as a reference-point and changed all actor-actor goal matches (i.e., goal incongruency) to extremely low, very low, low, medium, high, very high, and extremely high. Organizational theory qualitatively predicts that goal incongruency can increase the diversity of behavioral repertoires available to the project to meet the requirements imposed by the environment and therefore improve the project performance, e.g., reduce project cost (Weick, 1979). At the same time, organization theory indicates that too much goal incongruency can lead to time consuming arguments and undermine project performance, e.g., increase project cost (March and Simon, 1993). Hence, organization theory predicts a curvilinear relationship between goal incongruency and project cost. The Norne project manager's predictions were in accordance with organizational theory. Simulation results were stable and agreed qualitatively with organizational contingency theory[6].

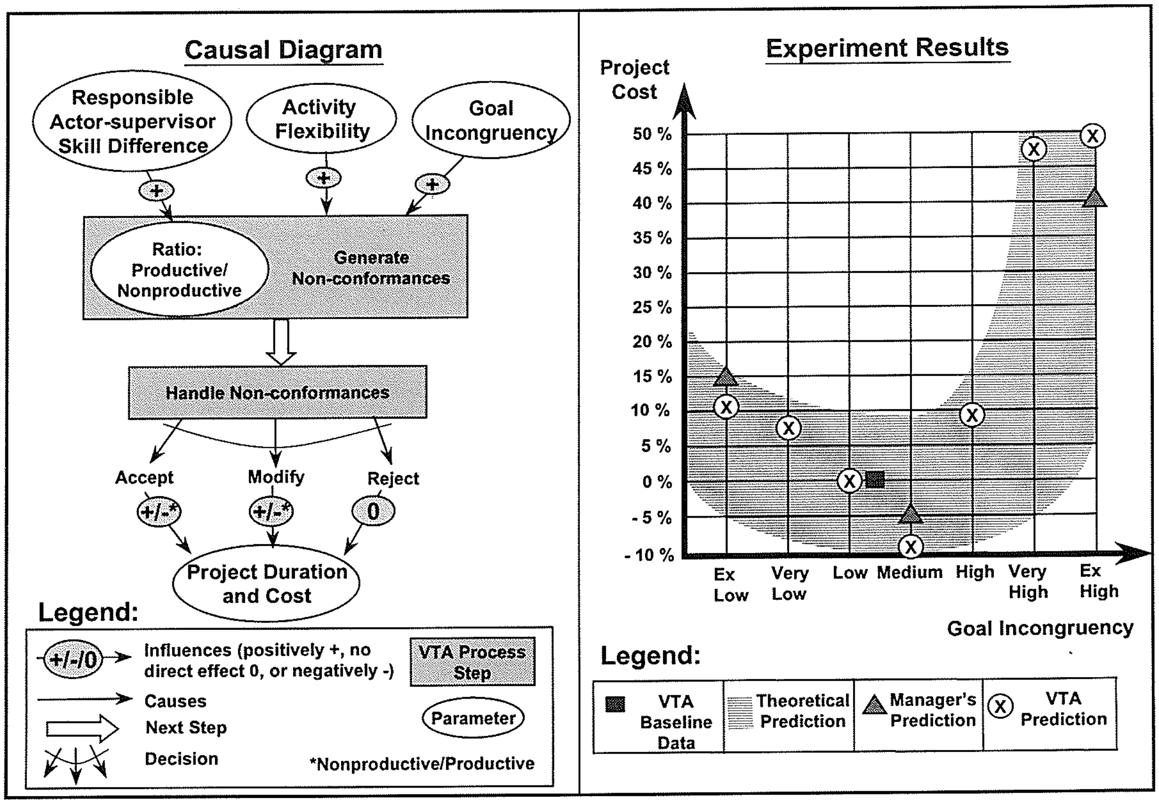

Figure 8: **The Effect of Responsible Actor-supervisor Skill Difference, Activity Flexibility, and Goal Incongruency on the Generation of Non-conformances (NC).** Activity flexibility and goal incongruency between the supervisor and subordinate determine whether a NC is generated. Once generated, the responsible actor-supervisor skill difference determines the effect that the NC exception is likely to have on project duration and cost. The right part of the figure shows the results from our simulation analysis. Our simulation experiments predicted that the project cost could have been better (by about 5-10%) if the project participants had had slightly more goal incongruency.

---

[6] To determine whether the simulation results were consistent with the manager's predictions, we performed t-tests, which treated manager's predictions as an estimate with a standard error of 5%; we used computed standard errors for the statistical simulation. The t-statistic was computed for extremely high, medium, and extremely low levels of goal incongruency. In all cases, the t-statistic was extremely small (maximum t=2.0), suggesting that the simulations were consistent with the manager's predictions. It should be noted that the simulation results were stable, with a coefficient of variation (CV) between 0.6 and 1.5 percent for all settings.

6.2 Information Exchange

The second communication process modeled in the VDT framework is information exchange. We consider two types of information exchanges: "FYI" and problem-solving information exchange. The behavioral consequences of information exchanges are different from those of technical errors and non-conformances. Unlike exception generation, this communication is not associated with technical errors and non-conformances directly, but it may affect the likelihood for exceptions further downstream. For example, because of a lack of specified interface information from the customer, the Pipe Tolerance Analysis activity used sketchy data about the connection tools between the "Xmas tree" and the satellite's pipes to perform tolerance analysis. The responsible actor for the pipe tolerance analysis communicated these initial results to responsible actors involved in interdependent activities because these actors needed the tolerance analysis data to continue their work. However, when more detailed interface data were given in the form of IDSs about the maximum forces and stiffness allowed from the connection tools, the Pipe Tolerance Analysis conducted a more in-depth analysis and more accurate data was relayed to interrelated activities. In consequence, the necessary "FYI" and problem-solving type of communication between pipe tolerance analysis and interdependent activities increased to account for the new pipe routing solution, and some rework was required.

Goal incongruency and interdependence strength determine whether a problem-solving communication is generated. Activity uncertainty and interdependence strength determine whether a "FYI" type of information exchange is generated. Together, these factors determine the number of information-related communications (Figure 9). The actor to whom the communication is directed can choose to attend or ignore the information. Non-attended communications lead to breakdowns in coordination, since important requests for information may not be heeded, or vital information may not be received. This may cause incompatibility in the design product and more errors further downstream. Therefore, the overall duration and cost of the work process will be affected.

We conducted a simple validation experiment on the Norne model using the VTA simulation to triangulate our model against the predictions from qualitative organizational theory and forecasts from the Norne project manager (Figure 9). We used the actual input model as a reference-point and changed all actor-actor goal incongruency values to extremely low, very low, low, medium, high, very high, and extremely high. Higher goal incongruency leads to more problem-solving communications. Because of actors' limited information-processing capacity, a higher number of communications will lead to more ignored communications (Simon, 1997a). Thus, coordination quality should decrease as a function of goal incongruency. However, a very high level of goal incongruency may lead to a breakdown in communication and ultimately to phenomena known as steamrolling and politicking (Pfeffer, 1981; Thomsen *et al.*, 1998a). Coordination quality should, therefore, decrease at a lower rater for very high levels of goal incongruency. Hence, organizational theory predicts a concave upward, monotonically decreasing relationship between goal incongruency and coordination quality. As with the two previous validation experiments, simulation results were stable and agree qualitatively with organizational contingency theory[7].

---

[7] To determine whether the simulation results were consistent with the manager's predictions, we performed t-tests, which treated manager's predictions as an estimate with a standard error of 5%; we used computed standard errors for the statistical simulation. The t-statistic was computed for extremely high, medium, and extremely low levels of goal incongruency. In all cases, the t-statistic was extremely small (maximum t=1.1), suggesting that the simulations were consistent with the manager's predictions. It should be noted that the simulation results were stable, with a coefficient of variation (CV) between 0.6 and 3.2 percent for all settings.

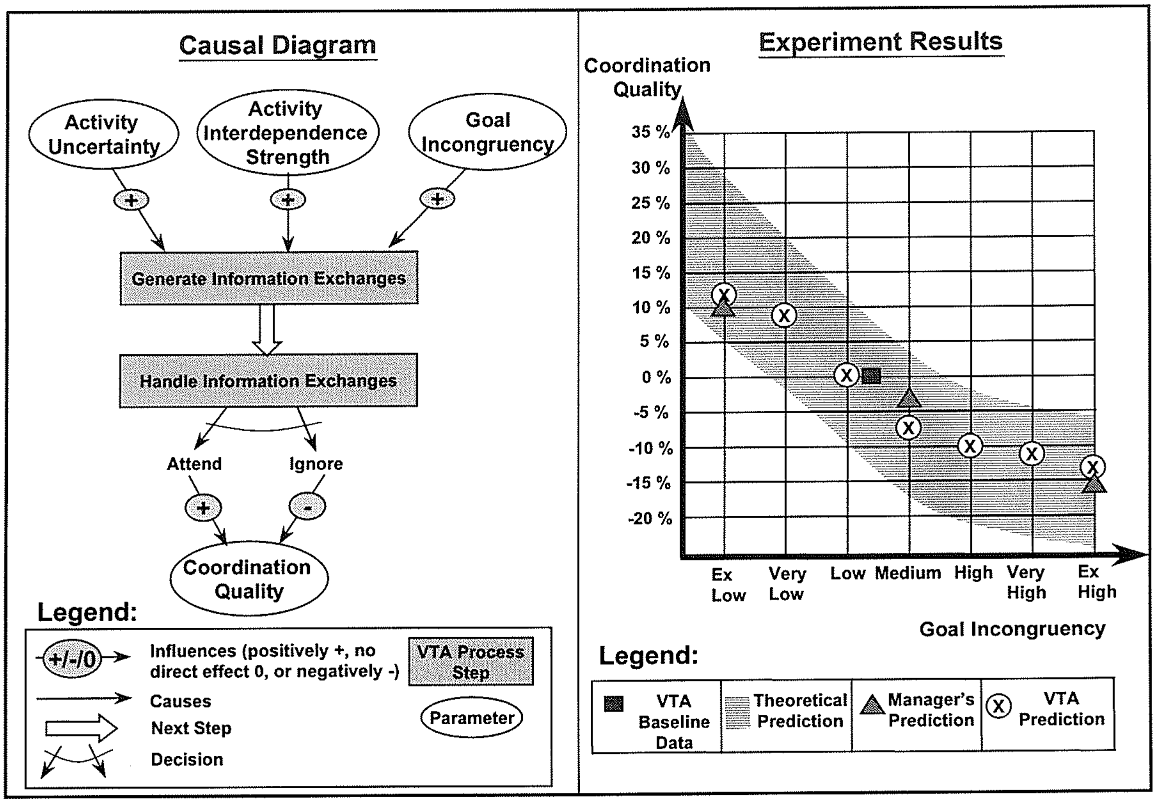

Figure 9: **The Effect of Activity Uncertainty, Interdependence Strength, and Goal Incongruency on the Generation of Information Exchanges.** Depending on how busy they are at the moment, actors can chose to ignore or attend to these communications, which ultimately will affect the performance of the project. The right part of the figure shows the results from our simple validation analysis. Our validation experiments show that the coordination quality could have been better (by about 10-15%) if the project participants had had less goal incongruency.

7. Discussion

We presented the four main anxieties of the Norne project manager in section 2.2. They pertained to (1) getting a measure of the level of interdependence between activities, (2) composing an efficient and effective project team, (3) minimizing error propagation, and (4) mitigating the effect of environmental uncertainty. Traditional project management tools and macro-contingency theory (Burton and Obel, 1995) are of limited help in developing and evaluating alternative organization and process designs with respect to these anxieties. Our representation and computational approach allow us to capture knowledge about the project, and thus model the project consistently. We focused on describing a representational scheme because clear representation makes knowledge acquisition easier. We linked our representation to information-processing behavior within the VTA discrete-event simulator and performed three simple experiments to illustrate and validate the behavior of the model.

Computer simulation can be useful in predicting the communication and coordination work load that arises in semi-routine, fast-paced design projects. We have taken the VDT simulation framework—originally used in routine design—and adapted it for use within less routine, faced-paced design. We portrayed engineers as professional actors with their own perspectives about the best solution approach to meet project requirements. For the Norne project, we described how we derived measures for activity complexity and interdependence strength, and how we estimated activity flexibility and uncertainty. From these measures the project manager gets an estimate of potential coordination problems and predictions of where and when consequent quality and schedule risks might arise.

Our contribution to engineering management and practice is that we have developed and presented an explicit methodology to derive key attributes of work processes (activity flexibility, complexity, uncertainty, and interdependence strength) and actors (goal incongruency) in semi-routine, fast-paced design projects. Our representation may be used without computational simulation for intuitive cognitive simulation by the project manager and as a tool for disseminating information that identifies and characterizes potential risk areas to project participants. However, we feel that our methodology gives most value when a model is simulated using the VTA discrete event simulator. The project manager can then systematically vary actor and work process parameters and semi-quantitatively compare the emergent project performance with his or her intuition. Our representation is not only suitable for studying differences within a given project, but can also be used to compare two projects by normalizing activity and actor attributes by the highest value present in the two projects.

Our contributions to computational organizational theory are that we have extended the existing VDT information-processing model to incorporate characteristics of less routine, fast-paced design and the notion of altruistic, but not entirely goal-congruent professional actors. We have tried to strike a balance between keeping our representation rich, but at the same time parsimonious enough, to maintain both theoretical transparency and modeling feasibility. Our framework simplifies how actor perspectives and priorities can be represented to support simulation, in contrast to decision-theoretic approaches that focus on gathering information about all alternatives for each design decision (Howard and Matheson, 1983). In our information-processing approach, we do not need to specify the characteristics of each alternative an actor considers in making a decision among alternatives. Instead, we estimate the flexibility of a particular activity and assume that each of the actors will select a solution approach based on his or her goal priorities. This avoids the complexity of decision-theoretic or utility-based representations of problems and allows us to focus on how different process and organizational designs affect communication and coordination in project organizations.

To be amenable to analysis in our framework, a project should first have relatively clear requirements. Second, project managers should understand work processes well enough so they can relate requirements to the process and assign activities to different, specialized individuals. Third, the interactions between activities must be derivable from requirements. While these assumptions do not apply to all projects or organizations, they apply well to many engineering design and product-development tasks as well as to organizations that are moving toward organizing their ongoing work processes as "projects" (Davidow and Malone, 1992; Hammer and Champy, 1993). For example, we have used our methodology within a medical organization and represented a protocol (i.e., a work process) for bone-marrow transplantation (Fridsma and Thomsen, 1997). We have also applied our methodology to the development of a new launch vehicle and a pyrovalve for positioning satellites in space (Thomsen *et al.*, 1998b; 1998c).

Within the Architecture/Engineering/Construction (A/E/C) industry, most work groups are organized in the form of project teams, and it has been common practice for project managers to design organizational structures and to select personnel through a trial-and-error adaptation approach (Tatum, 1984). Our representation of projects allows for the development and use of consistent and reliable organizational analysis tools that minimize the possibility of negative or unforeseen consequences inherent in a trial-and-error process. Computational modeling and simulation can provide managers with predicted outcomes prior to actual implementation. Our long-term goal is to enable the manager to accomplish, in an objective, explicit and quantitative fashion, what would normally be done in an intuitive manner or on the basis qualitative analysis of trial-and-error experience alone. Our research so far has focused on creating a clear representation for simulation, not so much on the simulation itself. More work is needed to validate the resulting simulation results. Our next step is to run suites of simulations to analyze the effect of different model input variables (e.g., activity flexibility and interdependence strength) and to validate the representation and the simulation on additional projects.

In the long run, we aim to refine and validate VTA so it can provide a new kind of analysis tool to enable true "engineering" of work processes and organizations.

8. Acknowledgements

We are grateful to the Norne Detailed Design Project Team who eagerly provided information and knowledge about engineering projects in general and the Norne Detailed Design Project in particular. We also thank L. C. Christensen's who helped in data collection and Dr. T. R. Christiansen for comments on earlier versions of this paper.

9. References Cited

Bonner, J. (1995), *Economic efficiency and social justice: the development of utilitarian ideas in economics from Bentham to Edgeworth.* Aldershot, Hants, England; Brookfield, Vt.: E. Elgar Pub.

Brown, S. L. and K. M. Eisenhardt (1997), "The Art of Continuous Change: Linking Complexity Theory and Time-paced Evolution of Relentlessly Shifting Organizations," *Administrative Science Quarterly*, 42(1), 1-34.

Burton, R. M. and B. Obel (1995), *Strategic Organizational Diagnosis and Design: Developing Theory for Application*. Boston: Kluwer Academic Publisher.

Carley, K. M. and M. J. Prietula (Eds.) (1994), *Computational organization theory.* Hillsdale, N.J.: Lawrence Erlbaum Associates.

Chatman, J. A. (1991), "Matching people and organizations: Selection and socialization in public accounting firms," *Administrative Science Quarterly* 36(3), 459-484.

Chiles, T. H. and J. F. McMackin (1996), "Integrating variable risk preferences, trust, and transaction cost economics," *Academy of Management Review*, 21(1), 73-99.

Christensen, L. C., T. R. Christiansen, Y. Jin, J. Kunz and R. E. Levitt (1996), "Modeling and Simulation in Enterprise Integration – A Framework and an Application in the Offshore Oil Industry," *Concurrent Engineering: Research and Application*, 4(3), 247-259.

Christensen, L. C., T. R. Christiansen, Y. Jin, J. Kunz and R. E. Levitt (1997), "Object-Oriented Enterprise Modeling and Simulation of AEC Projects," *Microcomputers in Civil Engineering*, 12, 157-170.

Christiansen, T. R. (1993*), Modeling the Efficiency and Effectiveness of Coordination in Engineering Design Teams*. Ph.D. Dissertation, Department of Civil Engineering, Stanford University, published as Det Norske Veritas Research Report No. 93-2063, Oslo, Norway.

Cohen, G. P. (1992*), The Virtual Design Team: An Object Oriented Model of Information Sharing in Project Teams.* Ph.D. Dissertation, Department of Civil Engineering, Stanford University.

Cyert, R. M and J. G. March (1992), *A Behavioral Theory of the Firm* (2nd edition). Cambridge, MA: Blackwell Publishers (1st edition 1963).

Davidow, W. H. and M. S. Malone (1992*), The virtual corporation: structuring and revitalizing the corporation for the 21st century.* New York: Edward Burlingame Books/HarperBusiness.

Donaldson, L. (1985), *In defence of organization theory: a reply to the critics.* Cambridge; New York: Cambridge University Press.

Drazin, R. (1990), "Professionals and Innovation: Structural-Functional versus Radical-Structural Perspective*," Journal of Management Studies,* 27(3), 245-263.

Duncan, R. B. (1972), "Characteristics of Organizational Environments and Perceived Environmental Uncertainty," *Administrative Science Quarterly*, 17(3), 313-327.

Eisenhardt, K. M. (1989a), "Agency Theory: An Assessment and Review," *Academy of Management Review*, 14(1), 57-74.

Eisenhardt, K. M. (1989b), "Building Theories from Case Study Research," *Academy of Management Review*, 14(4), 532-550.

Eppinger, S., D. E. Whitney, R. P. Smith, and D. A. Gebala (1994), "A Model-Based Method for Organizing Tasks in Product Development," *Research in Engineering Design*, 6, 1-13.

Fridsma, D. B. and J. Thomsen (1997), *Representing Medical Protocols for Organizational Simulation: An Information-processing Approach*. Report, Stanford University, Section for Medical Informatics, Report Number: SMI-97-0678.

Galbraith, J. (1973), *Designing Complex Organizations*. Reading, Mass.: Addison-Wesley Pub. Co.

Galbraith, J. (1977), *Organization Design*. Reading, Mass.: Addison-Wesley Pub. Co.

Ghoshal, S. and P. Moran (1996), "Bad for practice: A critique of the transaction cost theory," *Academy of Management Review*, 21(1), 13-47.

Hammer, M. and J. Champy (1993), *Reengineering the Corporation*. Harper Collins Publishers.

Hauser, J. R. and D. Clausing (1988), *The House of Quality*, Harvard Business Review, May-June, 63-73.

Howard, R. A. (1971), *Dynamic Probabilistic Systems Volume 1: Markov Models*. New York: John Wiley and Sons.

Howard, R. A. and J. E. Matheson (1983), *The Principles and Applications of Decision Analysis Volume 1: General Collection, Volume 2: Professional Collection.* Strategic Decisions Group.

Jin, Y. and R. E. Levitt (1996), "The Virtual Design Team: A Computational Model of Project Organizations," *Computational and Mathematical Organization Theory*, 2(3), 171-196.

Jurkovich, R. (1974), "A Core Typology of Organizational Environments," *Administrative Science Quarterly*, 19 (3), 380-394.

Kerzner, H. (1997), *Project management: a systems approach to planning, scheduling, and controlling* (6th edition). New York: Van Nostrand Reinhold.

Lawrence, P. R. and J. W. Lorsch with the research assistance of J. S. Garrison (1967), *Organization and environment: managing differentiation and integration.* Boston: Division of Research, Graduate School of Business Administration, Harvard University.

Locke, E. A. and G. P. Latham with contributions by K. J. Smith and R. E. Woo (1990), *A theory of goal setting and task performance.* Englewood Cliffs, N.J.: Prentice Hall.

Malone, T. W., K. Crowston, J. Lee and B. Pentand (1993*), Tools for inventing organizations: Toward a handbook of organizational processes.* Center for Coordination Science, Massachusetts Institute of Technology, Working Paper # 141.

March, J. G and H. A. Simon (1993), *Organizations* (2nd edition). Cambridge: Blackwell Publishers (1st edition 1958).

Masuch, M. and P. Lapotin (1989), "Beyond Garbage Cans: An AI Model of Organizational Choice," *Administrative Science Quarterly*, 34, 38-67.

Mock, M. and E. Morse (1977), "Size, Centralization and Organizational Adoption of Innovations," *American Sociology Review*, 42, 716-725.

Moder, J. J., C. R. Phillips and E. W. Davis (1983*), Project Management with CPM, PERT, AND Precedence Diagramming* (3rd edition). New York: Van Nostrand Reinhold (1st edition 1964).

Mohrman, S. A., S. G. Cohen and A. M. Mohrman (1995*), Designing Team-Based Organizations: New Forms for Knowledge Work.* San Francisco: Jossey-Bass Publishers.

Nass, C. I. (1986), "Bureaucracy, Technical Expertise, and Professionals: A Weberian Approach," *Sociological Theory*, 4, 61-70.

Osgood, C. E., G. J. Suci and P. H. Tannenbaum (1957), *The measurement of meaning.* Urbana: University of Illinois Press.

Pava, C. (1983), *Managing New Office Technology: An Organizational Strategy.* New York: Free Press.

Pfeffer, J. (1981), *Power in Organizations.* Marshfield, MA: Pitman.

Pfeffer, J. (1982), *Organizations and organization theory.* Boston: Pitman.

Pfeffer, J., (1996), *Understanding organizations: concepts and controversies*. Graduate School of Business, Stanford University, Research paper no. 1378.

Rosenschein, J. S. and M. R. Genesereth (1985), "Deals Among Rational Agents." IJCAI 85: *Proceedings of the Ninth International Joint Conference on Artificial Intelligence*. Distributed by Morgan Kaufmann Publ. Inc., Los Altos, CA, pp. 91-99.

Simon, H. A. (1956), "Rational Choice and the structure of the environment," *Psychological Review*, 63:129-138.

Simon, H. A. (1996), *The sciences of the artificial* (3rd edition). Cambridge, Mass.: MIT Press (1st edition 1969).

Simon, H. A. (1997a), *Administrative Behavior* (4th edition). New York: Macmillan (1st edition 1945).

Simon, H. A. (1997b), *Models of Bounded Rationality: Empirical Grounded Economic Behavior* (Volume 3). Cambridge, MA: The MIT Press.

Soelberg, P. (1967), *A Study of Decision-Making Choice*. Unpublished Ph.D. dissertation, Carnegie-Mellon University.

Steward, D. (1981), "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Transactions on Engineering Management*, 28, 71-74.

Tatum, C. B. (1984), "Organizing large projects: How managers decide," *Journal of Construction Engineering and Management*, ASCE, 110, 246-258.

Thompson, J. D. (1967), *Organizations in action: social science bases of administrative theory*. New York: McGraw-Hill.

Thompson, J. D. and A. Tuden (1959), "Strategies, Structures, and Processes of Organizational Decision," in J. D. Thompson and others (Eds.), *Comparative Studies in Administration*. Pittsburgh: University of Pittsburgh Press.

Thomsen, J., R. E. Levitt and C. I. Nass (1998a), *The Virtual Team Alliance (VTA): Extending Galbraith's Information-processing Model to Account for Goal Incongruency*. CIFE Working Paper #45, Stanford University.

Thomsen, J., J. C. Kunz and R. E. Levitt (1998b), *Designing Quality into Project Organizations through Computational Organizational Simulation*. CIFE Working Paper #46, Stanford University.

Thomsen, J., R. E. Levitt, J. C. Kunz and C. I. Nass (1998c), *A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations*. CIFE Working Paper #47, Stanford University.

Tung, R. L. (1979), "Dimensions of Organizational Environments: An Exploratory Study of Their Impact on Organization Structure," *Academy of Management Journal*, 22 (4), 672-693.

Weick, K. E. (1979), *The Social Psychology of Organizing* (2nd edition). Reading, MA: Addison-Wesley Pub (1st edition 1969).

Willems, P. (1988), *A functional network for product modeling*. PLI-88-18, IBBC-TNO, The Netherlands.