THE VIRTUAL TEAM ALLIANCE (VTA):

MODELING THE EFFECTS OF GOAL INCONGRUENCY IN SEMI-ROUTINE, FAST-PACED PROJECT ORGANIZATIONS

A DISSERTATION
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DOCTOR OF PHILOSOPHY

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Abstract

This dissertation introduces a new computational organizational model, called the Virtual Team Alliance (VTA), for investigating the effects of goal incongruency on the performance of semi-routine, fast-paced project organizations. I represent project participants as teleological professionals, and explicitly model goal incongruency between them. By modeling activity complexity, flexibility, uncertainty, and interdependence strength, my work process representation captures the effects of goal incongruency on the performance of semi-routine, fast-paced projects.

Because tasks in the VTA model are flexible, differences in goals may influence which solution approach project participants prefer; thus, goal incongruency can have profound implications for the performance of project teams. VTA actors comprise a complex system that is endowed with fragments of canonical information-processing micro-behavior. VTA integrates economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior with respect to information processing in the presence of goal incongruency. The canonical micro-behaviors in VTA include monitoring, selective delegation of authority, exception generation, searching for alternatives, clarifying goals, steamrolling, and politicking. The VTA model simulates the micro-level communication and coordination behavior of actors within the organization, including the impact of goal incongruency between individual actors, in order to determine the emergent, aggregate project behavior and performance. To Galbraith's sociological analysis, based on information-processing "organizational physics," I add new "organizational chemistry" notions based on social psychological and economic agency theories.

VTA generates useful and measurable emergent quantitative performance predictions regarding the efficiency and quality of a project's configuration of work processes and organizational structure. The model produces two measures of efficiency: project duration and total salary cost; and three measures of work process quality: problem-solving quality, coordination quality, and decision-making quality.

I validated my model retrospectively on an offshore field development project, contemporaneously on two portions of an ongoing aerospace launch vehicle project, and prospectively on a project aimed at developing a new generation of pyrovalves for positioning satellites in space. I demonstrated that the VTA micro-contingency theory makes predictions that are both theoretically and practically interesting.

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My three and a half years at Stanford University have really been mind-expanding. Several wonderful people have contributed to make my Ph.D. study delightful and exhilarating.

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While pursuing a Ph.D. at Stanford University does not compete in cost with atom smashing or moon shooting, it is not inexpensive. Thanks to generous financial support from Det Norske Veritas, The Norwegian Research Council, The National Science Foundation, The Fulbright Foundation, The American-Scandinavian Foundation, and Jansons Legat, the limit on my rate of Ph.D. progress has been fixed not by my budget, but by my own capacity to generate fertile ideas.

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CHAPTER I

Introduction

This introductory chapter presents the motivating problem, a set of research questions, the current state of knowledge and its limitations, and my extensions of the current state of knowledge. The chapter concludes with an integration of the general theme of my research and the relationships among the autonomous papers that constitute chapters II, III, IV, and V.

1. The Problem of Investigation

The dominant approach for studying performance in multi-constituency project teams has been grounded in the transaction-cost framework (Williamson, 1979). This theory focuses on the relationship among consumers and suppliers and the contracts, which regulate their transactions. In this dissertation, I have chosen to focus on the constituents of a project team, seeking to analyze project team performance in terms of the diversity of opinions or preferences between the participants or "actors." Individual preferences and beliefs concerning solutions to project goals are often a product of the particular organization or profession to which the individual belongs (Drazin, 1990). In turn, these preferences and beliefs determine how actors will weigh different factors and rank alternatives for conducting work. Since most tasks in projects are affected by decisions that take into consideration trade-offs among such factors as cost, duration, and quality, the fact that actors may choose different solutions to problems as a result of discrepant individual priorities has profound implications for the performance of project teams. I refer specifically to these differences in priorities between actors as the phenomenon of "goal incongruency."

The problem of goal incongruency is exacerbated in large engineering projects by the sheer complexity of modern engineering artifacts. The need for high levels of interaction among diverse groups (e.g., disciplines, departments, subcontractors) prohibits organizations from simply decomposing tasks and responsibilities and assigning them to strictly delineated departments or groups (Simon, 1996). Consequently, not only must organizations deal effectively with goal incongruency problems arising within supervisor-subordinate relationships, but they must also negotiate goal incongruency problems arising in lateral relationships between peers working on interdependent activities.

Many technology-based industries have tremendous pressure to get their products out faster. For example, the aerospace industry is confronting an increasingly competitive environment brought on by overseas competition and reduced domestic demand from the U.S. military. Much of the work is outsourced to external component suppliers whose goals may be incongruent with those of the prime contractor. In addition, firms have shortened work plans by taking many activities that have traditionally been scheduled sequentially and executing them in parallel. In such fast-paced projects, the habitual character of routine activities is lost. The project team needs work process flexibility to come up with solutions to tightened and challenging performance targets (Brown and Eisenhardt, 1997). Work process flexibility means that an actor has a range of potential solutions, all of which will meet the project goals. Actors have to make a choice among solutions. Interdependent, goal-incongruent actors may prefer different solutions. As a consequence, they engage in task conflicts that need to be resolved constructively by collaboration or by hierarchical decision making.

2. Research Questions

The basic idea underlying my research is that goal incongruency affects the local interaction between a supervisor and a subordinate as well as the local interaction between interdependent peers. These interactions may have significant impact on project cost, duration, and quality (i.e., money, time, and the number of engineering change orders). An example of a supervisor-subordinate interaction pattern is the level of managerial checking. A supervisor perceives the subordinate to be a perfectionist (a person who focuses on quality manifested through a beautiful engineering design). If the most important project goal is to finishing on schedule, the supervisor will tend to check the subordinate's work more often and stringently to ensure that the project goals will be met.

My research asks the following questions (Thomsen, 1995): *(1) As the level of goal incongruency between actors varies, how does it moderate the effect of organizational variables on emergent project performance? (2) What are the behavioral mechanisms that produce these emergent project performance effects?*

In a nutshell, my research will advance our understanding of the interplay between goal incongruency and organizational performance.

3. The Current State of Knowledge and its Limitations

Project management techniques, such as the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) cannot give practical answers to the problems brought about by goal incongruency for three reasons. The first reason is that CPM assumes an idealized situation in which concurrent activities for different deliverable parts of the project are independent and uncoupled. Earlier computational models such as the Virtual Design Team (VDT) (Jin and Levitt, 1996) address this shortcoming. Second, CPM/PERT models also view project participants as "omnipotent clairvoyants" who always act (they do not interact!) in perfect harmony with the project plan. Third, they assume there is only one way to perform the tasks on the project (Moder *et al.*, 1983). In other words, neither CPM/PERT nor VDT considers goal incongruency between project participants and how incongruent goals can create conflict in the face of task flexibility.

Based on models demonstrating that deviation from managerially prescribed goals by subordinates will necessitate additional coordination and communication efforts to resolve the discrepancies (Eisenhardt, 1985, 1989; Levinthal, 1988; Milgrom and Roberts, 1992; Ouchi, 1979), conventional management and economic theories assume that goal incongruency is categorically detrimental to performance. These theories posit that goal incongruency should be unequivocally discouraged.

New data from experiments in social psychology indicate that an intermediate level of goal incongruency may have potentially positive effects on group problem-solving performance (e.g., Amason, 1996; Jehn, 1995; Pelled, 1996; Watson *et al.*, 1993; Weick, 1979). On a micro-organizational level, theorists hypothesize that goal incongruency confers two distinct advantages. It forces actors to consider a wider range of possible solutions to a problem, which increases the likelihood that a more ideal solution will be found. Moreover, it leads to a greater understanding and clarification of the trade-offs associated with each solution under consideration, and encourages actors to formalize their knowledge of these trade-offs implicitly or explicitly into a "goal trade-off table." Shared goal trade-off beliefs among project participants can be viewed as a common set of values or a shared culture. The existence of shared values or culture is now widely viewed to increase efficiency by serving as a guidepost or touchstone that allows actors to make decisions more quickly and consistently when similar problems arise further downstream.

The ability of researchers to develop practically applicable insights from the growing body of literature on goal incongruency is hindered by the fact that most experimental data has been generated from studies of dyadic relationships. Experiments involving larger organizations are limited by the inability of the human mind to extrapolate from a single relationship to predictions regarding the emergent effects of goal incongruency in a complex, non-linear web of relationships. The logistical obstacles to conducting social psychological experiments on large-scale organizations have hindered experiments by organizational researchers, so the conversion of theoretical knowledge about goal incongruency into practical knowledge of how to manage organizations has yet to be accomplished. The dearth of practical insights produced by the research on goal incongruency is further compounded by the lack of research on the relationship between goal incongruency and organizational contingencies, such as the level of interdependence, work process flexibility, and preference for micro-management.

My research can be viewed as an attempt to bridge this gap by providing an analytical tool to help project managers balance organizational design and management policies in such a way that optimum performance is achieved for any given level of goal incongruency.

4. Extensions to the Current State of Knowledge

In my effort to provide managers with the means for evaluating the efficacy of different management policies under different conditions of goal incongruency, I believe it necessary to extend the information-processing model of organizational behavior. In light of the many variables that must be considered, as well as my intention to study the emergent effects of goal incongruency arising from the interaction of many actors, I chose to implement my framework through discrete event simulation models. Computer simulation of events allows for both more complex what-if experimentation to be pursued than is possible with mathematical models and for more control than is possible with experiments in the real world (e.g., Carley and Prietula, 1994).

Relying on organizational theories developed in the 1970s, when speed and flexibility were less relevant for organizational success than they presently are for firms, organizational simulations have been used in the organizational sciences to improve the design of real-world projects that perform *idealized, routine* work processes. To expand the range of applicability of computational organizational model, I relax these assumptions and combine field insights with economic agency theory and sociological and social psychological theories of organizational design to describe rich repertoires of "canonical" micro-behavior in real-world, fast-paced product development projects. In my Virtual Team Alliance (VTA) model, actors are endowed with fragments of canonical micro-behavior with respect to goal incongruency and, then assembled into networks of tasks and actors to represent real-world tasks and organizations.

The less routine nature of fast-paced work processes means that decision making requires *judgment* (Thompson and Tuden, 1959) and *interpretation* (Pava, 1983) by the professionals who carry it out. I therefore represent project participants, “actors,” as teleological professionals with potentially incongruent goals. In addition, my work process representation captures the fact that less routine work includes flexibility that may result in more complex exceptions than the sort characterized by Galbraith (1977).

In developing the conceptual extensions for VTA, I have extended existing contingency theory (Thompson, 1967) and Galbraith’s information-processing theory (Galbraith, 1973, 1977). I claim that these extensions create a new theoretical basis for my model of semi-routine, fast-paced projects consisting of professionals from multiple disciplines. Galbraith and other contingency theorists focus on organizational behavior at the level of the organization itself, and do not concern themselves with the internal dynamics of the organization. Goal incongruency, however, surfaces in the dyadic relationships between individual actors, and it is only at this level that one can apply the findings garnered from economic agency theory and social psychology about the potentially positive as well as negative effects of goal incongruency. Given my need to create a model for goal incongruency that considers its local influence on the internal micro-behavior of individual actors within organizations, I have extended contingency theory to develop a micro-contingency model of goal incongruency and organizational behavior. My VTA model takes actors and the relationship between pairs of actors as the fundamental unit of analysis.

Within the larger framework provided by Galbraith's information-processing model, I incorporate and operationalize behavioral and organizational theories, which analyze behavior at the level of individual actors and relationships. These theories cover the behavior of actors embedded in vertical dyadic relationships in the organizational hierarchy, as well as the behavior of peer actors working on interdependent tasks. I depict organizational actors as relatively simple, goal-oriented, information processors and communicators, with finite or "boundedly rational" capacity (March and Simon, 1993). Their work is choreographed by

- relatively abstract, flexible, sequentially and reciprocally interdependent information-processing activities assigned to them (Thompson, 1967), and
- organizational structures that reactively handle exceptions from pre-planned activities in the spirit of Galbraith (1973, 1977) and proactively monitor the behavior of subordinates (Ouchi, 1979; Eisenhardt, 1985).

The past VDT work operationalized aspects of Galbraith's information-processing view of organizations. VTA extends Galbraith's framework to address less routine tasks with some flexibility in how they are performed. Since tasks are now flexible, differences in goals may influence which solutions project participants prefer so that goal incongruency matters. VTA integrates economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior with respect to information processing in the presence of goal incongruency. To Galbraith's sociological analysis, based on information-processing "organizational physics," I add new "organizational chemistry" notions based on social psychological and economic agency theories.

5. A Reader's Guide to the Dissertation

Since the four papers (chapters II, III, IV, and V) will be published as autonomous journal articles, the reader should not be bound by the sequence I have imposed on them, but yet should be aware that the sequence is not arbitrary. Even though the four chapters are autonomous, there is a conjunctive relationship among them. The first chapter focuses on representation, the second chapter focuses on reasoning, and the third and fourth chapters focus on the output measures of my model. Representation, reasoning and model output measures are all essential building blocks in a real-world computational model of the effects of goal incongruency on project team performance (Figure 1). Please note that although the four papers are co-authored, I drafted the full text and received the same amount of comments from the listed co-authors that I would have had they been reviewing draft chapters of a traditional dissertation.

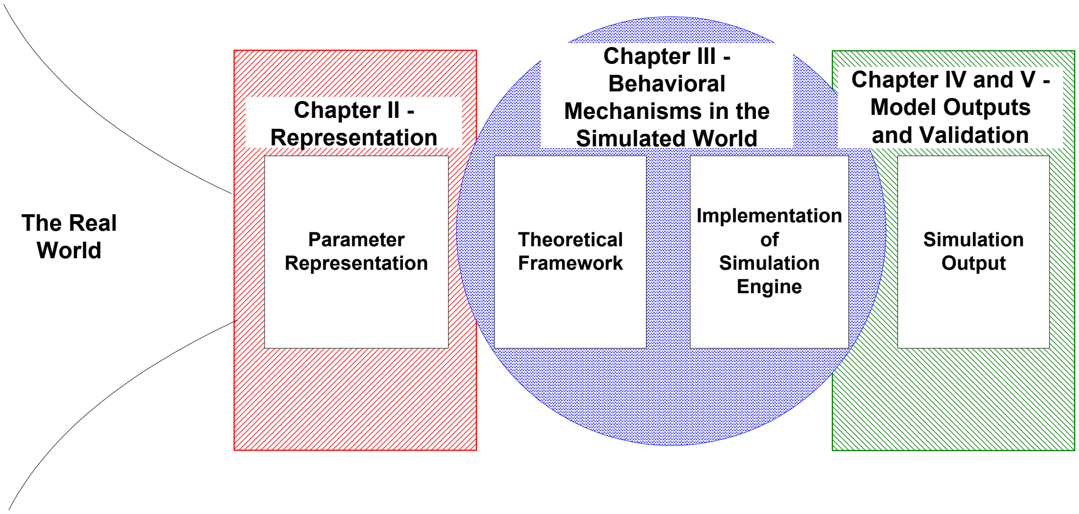

Figure 1: **Computational Modeling and Simulation.** It is impossible and unattractive to represent the real world in its entirety. Based on the questions one wants to investigate, one extracts and simplifies the most important aspects of reality. The problem of investigation suggests a sufficient, not comprehensive, representation of the real world for the phenomena being studied. This parameter representation is linked to behavior in the simulation model. The behavior in the simulation model is, of course, less complex than the real world. It is created at an intermediate level, which is neither so complex that the model becomes ponderous and inefficient, nor so abstract and simplistic that the model produces no practical insights. The reasoning or behavior of the simulation model determines the final model output. The difference between the actual project outcome and the simulated project outcome is a measure of how accurate the computational model is in running simulations and making performance predictions.

Chapter II describes my extensions of Thompson's (1967) contingency theory and develops an extended theory of coordination in concurrent product development projects.

Chapter III focuses on the application of research on organizations in order to determine how and under what condition goal incongruency will affect organizational performance. I develop the Virtual Team Alliance (VTA) model that extends Galbraith's information-processing model to account for goal incongruency.

Chapter IV expands on the utility and applicability of *holistic* and *universal* TQM prescriptions by incorporating newer insights from computational organizational modeling to develop a more powerful *detailed* and *contingent* approach to designing quality into organizations.

Chapter V develops an innovative validation trajectory strategy for complex computational emulation models. I present a validation trajectory that includes: (1) computational synthetic experiments, (2) retrospective validation and comparison with manager's "what-if" predictions, (3) contemporaneous validation, and (4) prospective validation with intervention.

I conclude my dissertation with a summary of my practical and theoretical contributions and my suggestions for future work.

CHAPTER II

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

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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

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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 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

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[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.

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).

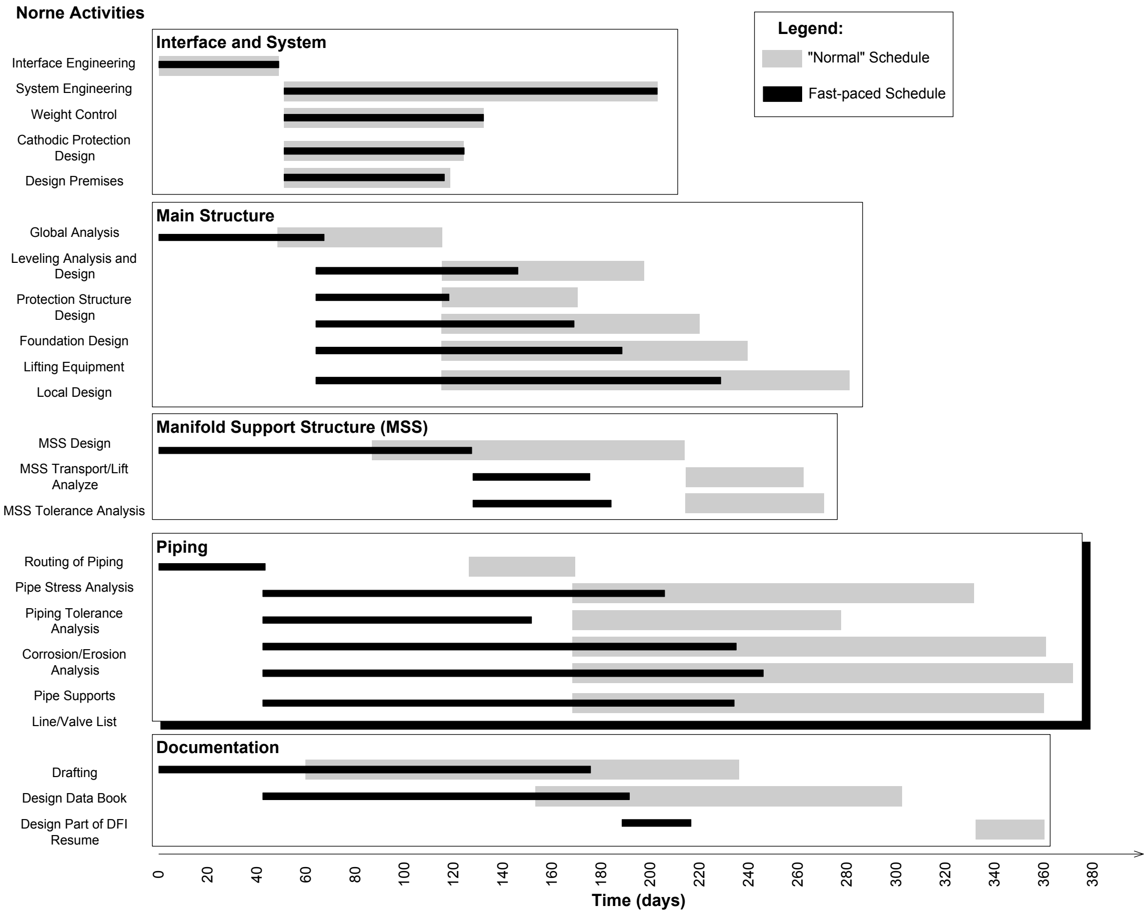

***Figure 1:* The Norne Project Gantt Chart**. The thin dark bar represents the fast-paced Norne schedule, and the thicker, shaded bar overlaid on each thin bar represents a less fast-paced or more "normal" schedule for this type of project. The overall scope of work can be divided into four main blocks 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.,

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[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.

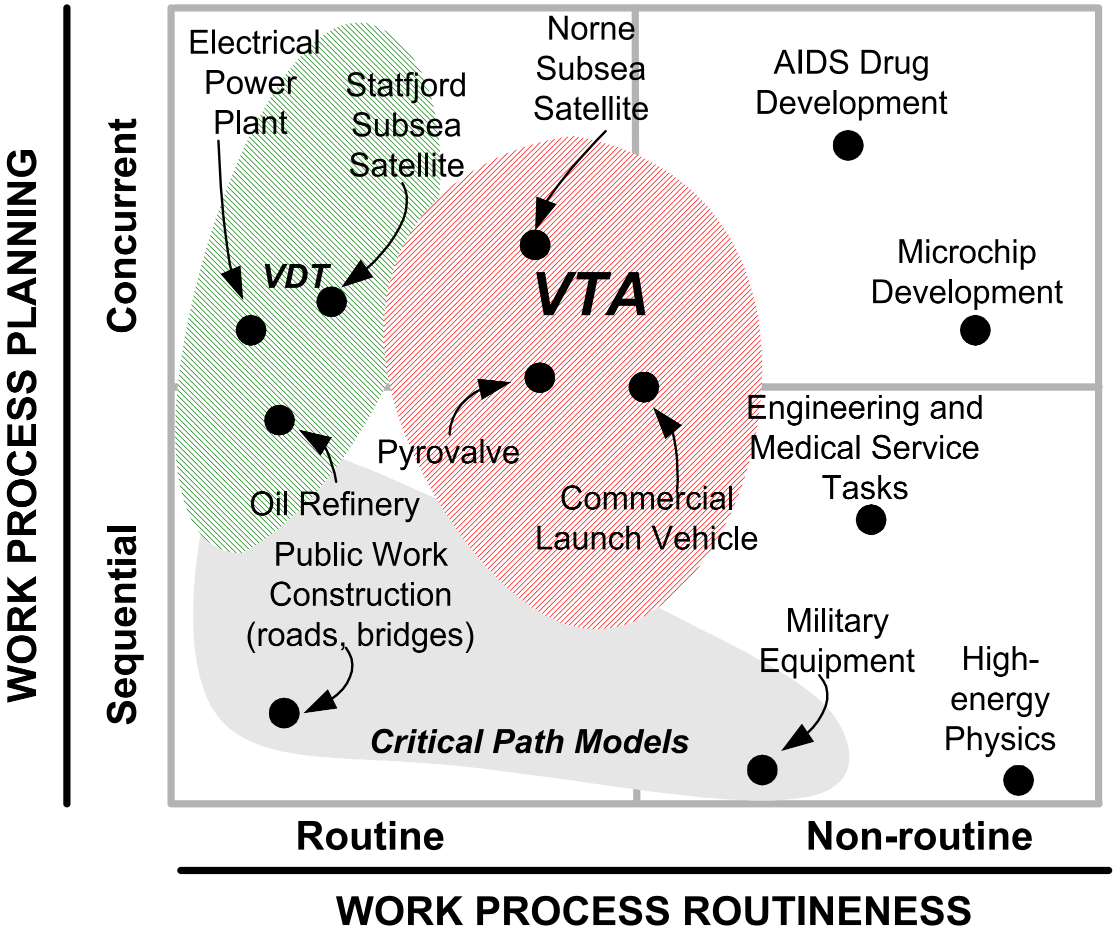

Figure 2: **A Qualitative Comparison between CPM/PERT, VDT, and our VTA Model.** It shows the "organizational space" of applicability of different project management tools (bubbles).

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

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[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.

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 ($\geq$)," 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.

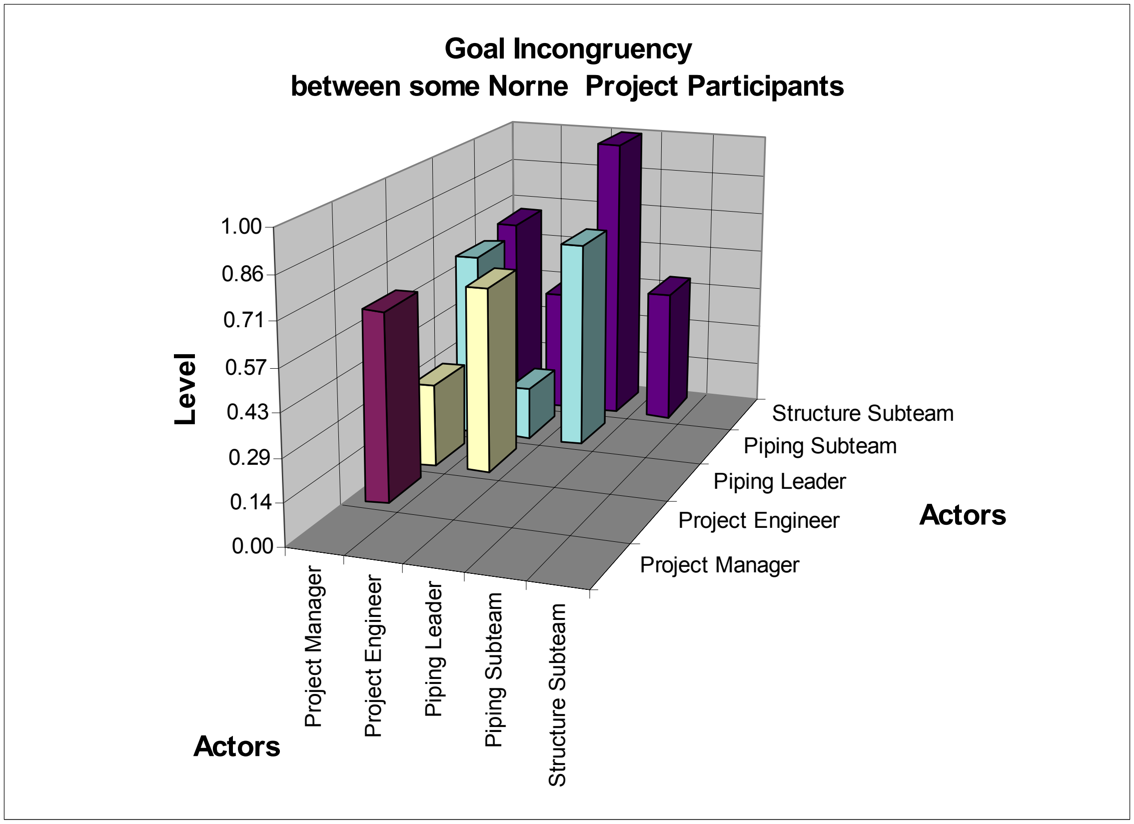

Figure 3: **The Level of Goal Incongruency between Different Groups within the Norne Project**. The values have been normalized, so that the actors with the highest incongruency have a value of 1.0. We see, for example, that the goal incongruency between the Project Manager and the Project Engineer is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

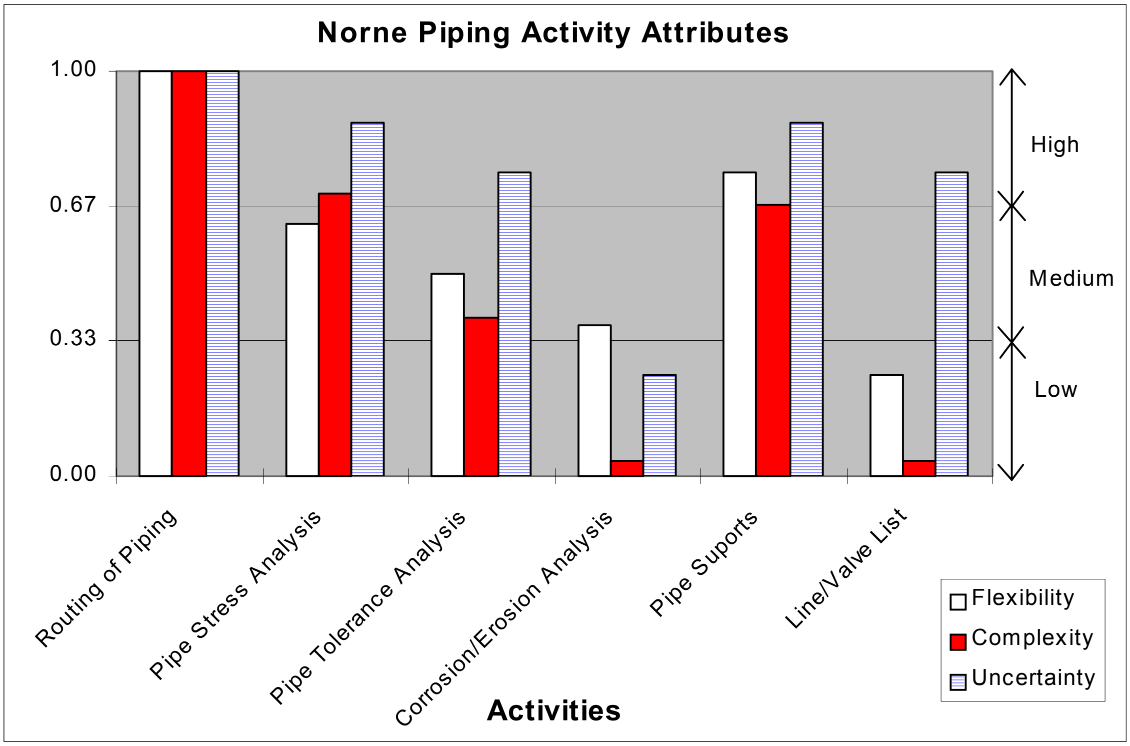

Figure 4: **Activity Flexibility, Complexity, and Uncertainty for the Piping Design Activities**. The activities with the highest flexibility, complexity, or uncertainty have a value of 1.0. We then translated the normalized values to symbolic ordinal values high, medium, or low.

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.

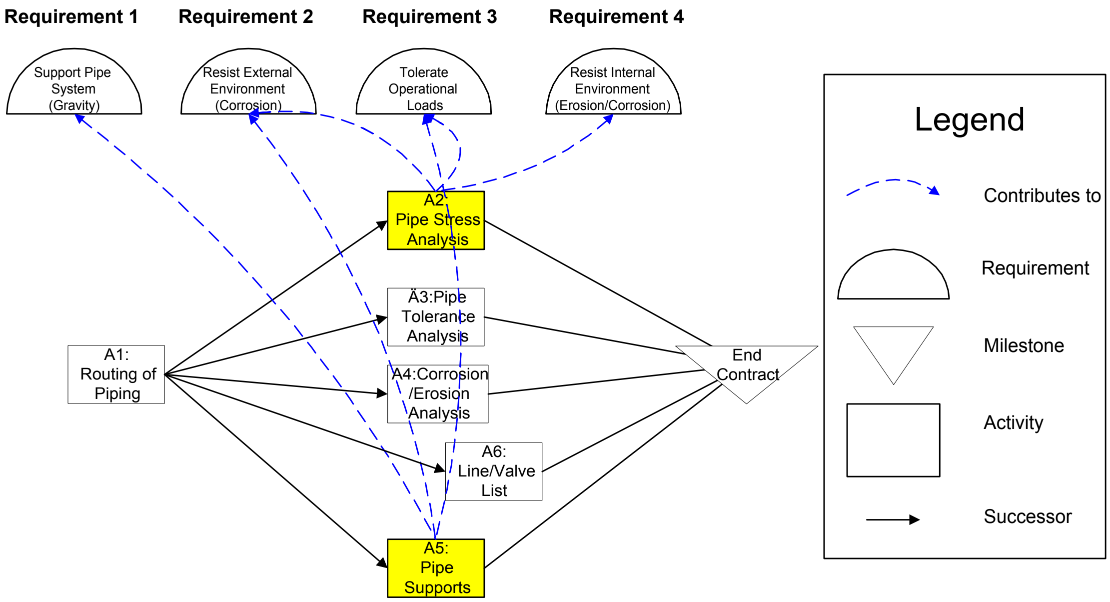

Figure 5: **Linking Activities to Requirements.** A portion of the project plan for the Norne Subsea Satellite Design showing the requirements for two activities within the piping part—"Pipe Stress Analysis" and "Pipe Supports." Requirement 1—"Support Pipe System" (Gravity) is solved by the weight evaluations 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:

$$\text{Complexity}_{A5} = \sum_i Complexity_{R_i}\ ,\ \forall \text{ requirements } (R_i) \text{ of } A_5$$
$$= \text{Complexity}_{R1} + \text{Complexity}_{R2} + \text{Complexity}_{R3}$$
$$= f_5 + (f_2 + f_5) + (f_2 + f_5) = 2f_2 + 3f_5 = 10 + 18 = 28 \tag{1}$$

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:

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

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

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

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.

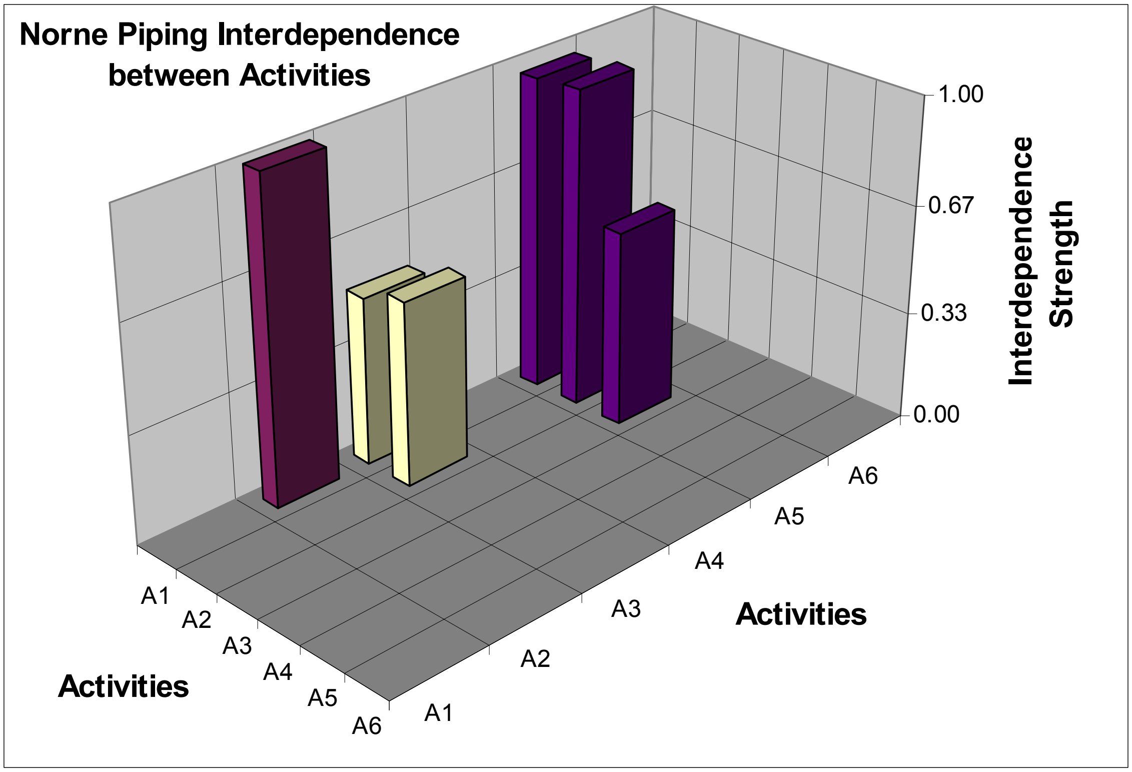

Figure 6: **The Interdependence Strength between Activities.** The 3-D graph shows the interdependence strength between each pair of activities. Routing of Piping (A1) and Pipe Stress Analysis (A2) are most interdependent, whereas Erosion/Corrosion Analysis (A4) and Line/Valve List (A6) are least interdependent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

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

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**.
- $\mathbf{I}$ is a m by m identity matrix.
- $\mathbf{F}$ is a n by n diagonal matrix with activities located on the rows and columns. The activity flexibility is represented in the diagonal.
- $\mathbf{H}$ 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].

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[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.

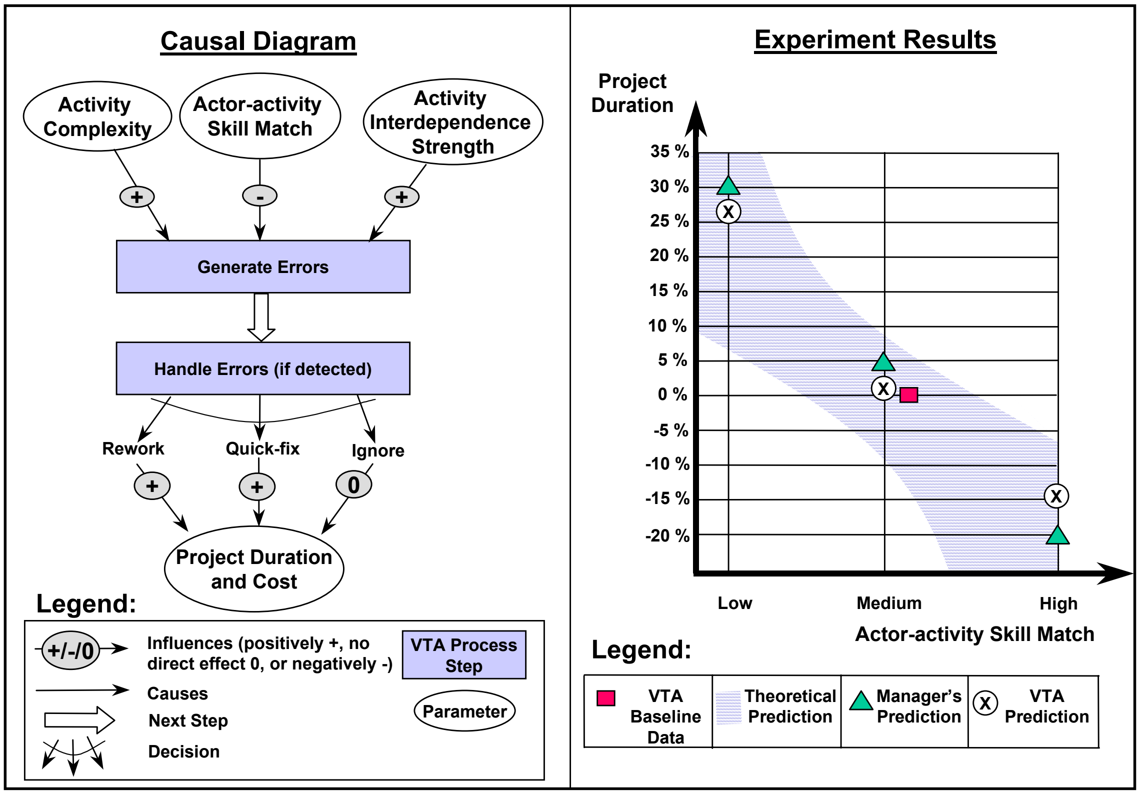

***Figure 7*: The Effect of Activity Complexity, Actor-activity Skill Match, and Interdependence Strength on Project Performance.** The activity complexity and actor-activity skill match determine the likelihood for a technical error to occur. Activity interdependence determines whether the technical 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].

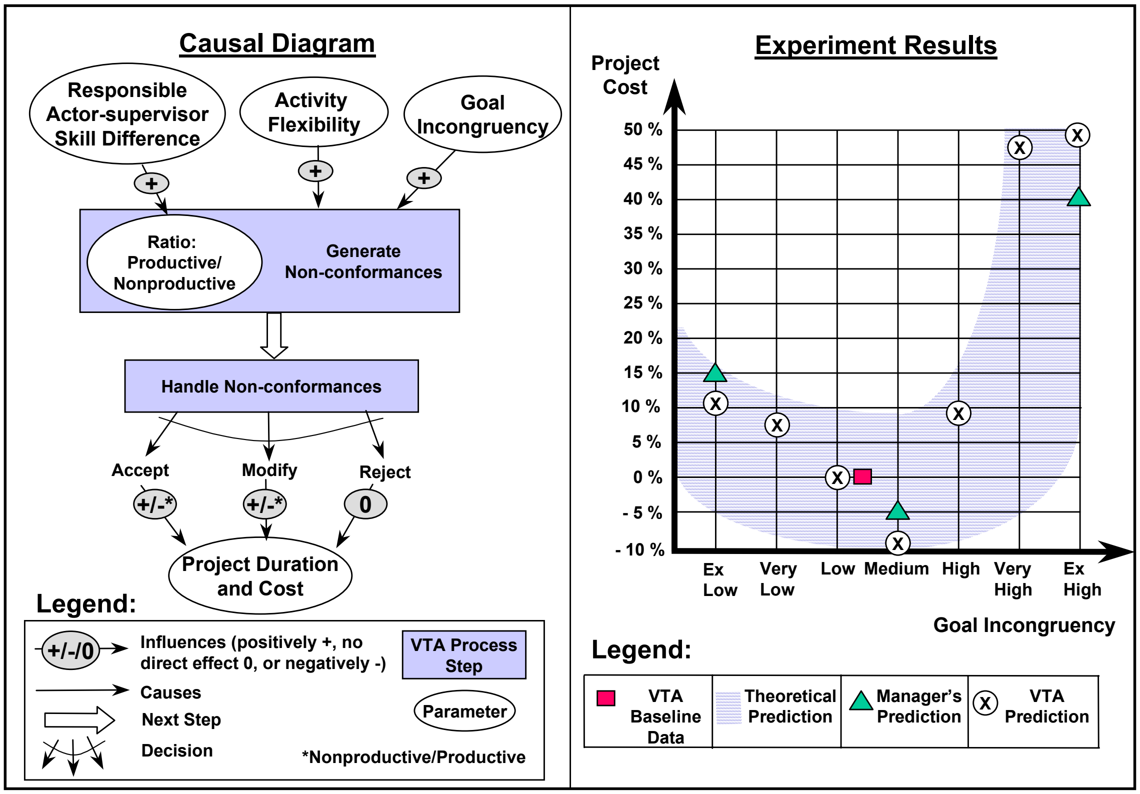

Figure 8: **The Effect of Responsible Actor-supervisor Skill Difference, Activity Flexibility, and Goal Incongruency on the Generation of Non-conformances (NC).** Activity flexibility and goal incongruency between the supervisor and subordinate determine whether a NC is generated. Once generated, the 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.

6.2 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

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[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.

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].

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[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.

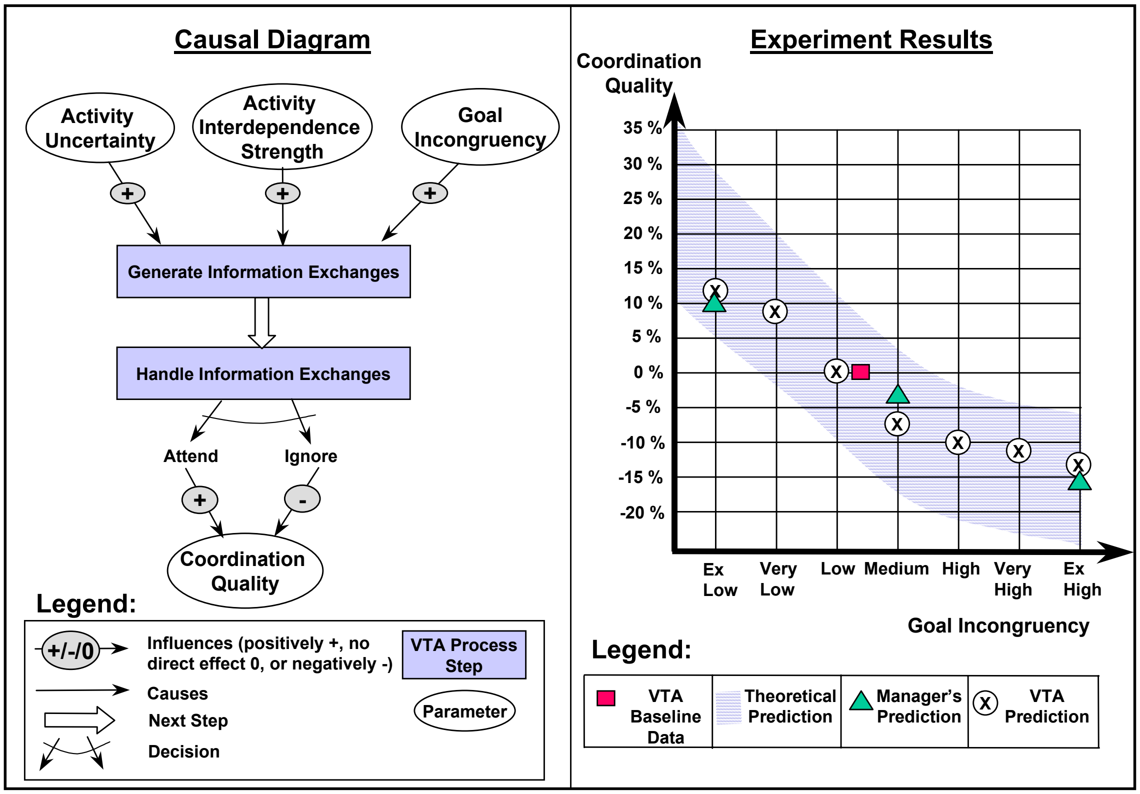

Figure 9: **The Effect of Activity Uncertainty, Interdependence Strength, and Goal Incongruency on the Generation of Information Exchanges.** Depending on how busy they are at the moment, actors can chose to ignore or attend to these communications, which ultimately will affect the performance of the 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

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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” *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 & R. Levitt (1996), “Modeling & Simulation in Enterprise Integration – A Framework & an Application in the Offshore Oil Industry,” *Concurrent Engineering: Research & Application*, 4(3), 247-59.

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, Dept. of Civil Engineering, Stanford Univ., 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, Dept. of Civil Eng., Stanford Univ.

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, MA.: Addison-Wesley.

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.

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. and J. Matheson (1983), *The Principles & Applications of Decision Analysis Vol.1: General Collection, Vol.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 Mathem. Org. 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 Univ.

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.

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). Camb., MA: MIT Press.

Simon, H. A. (1997a), *Administrative Behavior* (4th ed.). NY: Macmillan (1st ed. 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 Comp. Org. Simulation.* CIFE WP #46, Stanford University.

Thomsen, J., R.Levitt, J.Kunz and C.Nass (1998c), *A Proposed Trajectory of Validation Experiments for Comp't'l Emulation Models of Orgs*. CIFE WP #47, Stanford Univ.

Tung, R. L. (1979), "Dimensions of Organizational Environments: An Exploratory Study of Their Impact on Organization Structure," *Academy of Mgmt. J.*, 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.

CHAPTER III

The Virtual Team Alliance (VTA): Extending Galbraith's Information-processing Model to Account for Goal Incongruency[8]

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Abstract

This paper introduces a new computational organizational analysis and design model, called the Virtual Team Alliance (VTA), that builds on the Virtual Design Team (VDT) (Jin and Levitt, 1996). VDT operationalized aspects of Galbraith’s information-processing view of organizations, but it assumed tasks to be routine and project participants to have completely congruent goals. VTA extends Galbraith's framework implemented in VDT in two ways: (1) it addresses less routine tasks with some flexibility in how they are performed, and (2) it treats project participants as teleological professionals with potentially incongruent goals. Because tasks in the VTA model are flexible, differences in goals may influence which solution approach project participants prefer; thus, goal incongruency can have profound implications for the performance of project teams. VTA integrates economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior with respect to information processing in the presence of goal incongruency. We describe how VTA actors comprise a complex system that is endowed with fragments of canonical information-processing micro-behavior. The canonical micro-behaviors in VTA include exception generation, monitoring, selective delegation of authority, searching for alternatives, clarifying goals, steamrolling, and politicking. The VTA model simulates the micro-level communication and coordination behavior of actors within the organization, including the impact of goal incongruency between individual actors, in order to determine the emergent, aggregate project behavior and performance. To Galbraith’s sociological analysis, based on information-processing "organizational physics," we add new "organizational chemistry" notions based on social psychological and economic agency theories.

Key Words and Phrases: Agency Theory, Computational Organizational Design, Contingency Theory, Goal Incongruency, Information Processing, Professionals, Project Organizations, Semi-routine Tasks.

1. Introduction

Many organizations are beginning to organize their ongoing work processes as “projects” (Davidow and Malone, 1992; Hammer and Champy, 1993). Although project teams can be effective and are often the most efficient means by which a firm can organize its

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operations to meet production goals, they still give rise to a host of organizational design problems for managers.

Project organizations engaged in rapid deployment of new products with significant technical content shorten work plans by taking many activities that have traditionally been done sequentially and executing them in parallel. In these challenging fast-paced product development projects, the habitual character of the previously routine activities is lost. The project team needs work process flexibility to come up with solutions to tightened and challenging performance targets (Brown and Eisenhardt, 1997). Work process flexibility gives project participants a range of potential solution approaches, all of which will meet the project requirements. Project participants thus have to make a choice among solution approaches. Interdependent, goal-incongruent project participants may prefer different solution approaches. Consequently, they develop task conflicts that need to be handled by collaboration or by hierarchical decision making. Complex exceptions, extending beyond the information shortfalls characterized by Galbraith (1977), are endemic to this kind of semi-routine work. Executing projects concurrently increases the impact of exceptions, and, therefore, greatly increases the volume of coordination and rework. Effective and efficient organizational designs can mitigate the increase in coordination and rework as projects become increasingly fast-paced.

Extant theories of organization from sociology, political science, social and cognitive psychology and economics are of limited use in describing, predicting, or intervening in, these “agile,” knowledge-networked organizations. Within the growing Computational Organizational Science (COS) community, there has been some progress in using computers to model and analyze today’s increasingly agile organizations executing interdependent and concurrent knowledge work (e.g., Carley and Lin, 1995; Jin and Levitt, 1996). Researchers are attempting to advance organizational analysis and design from its current holistic and heuristic approach to one of “model-based reasoning.” Organizational analysis tools such as the Virtual Design Team (VDT) model participants as information-processing entities with skill sets and experience and explicitly model lateral interdependencies between activities. VDT offers powerful new capabilities for modeling and analyzing fast-paced work processes and the project teams that execute them. However, VDT does not include variables, which may be critical in multidisciplinary and multi-organizational (cultural), agile project organizations. VDT assumes that all project participants have congruent goals, and it makes assumptions about the routineness of the activities themselves that make it applicable only to relatively routine work processes. VDT is based on the premise that coordination work takes time. Coordination work delays project completion, increases costs, and affects work process quality. For tasks in which coordination is crucial, empirical evidence abounds that, even though coordination can contribute to overloading actors, coordination may also result in better solutions in terms of cost and duration. Building off the VDT framework, the primary contribution of this paper is a new computational organizational analysis tool, the Virtual Team Alliance (VTA). VTA extends Galbraith's framework to model the behavior of project participants as teleological professionals with potentially incongruent goals and to address less routine tasks with some flexibility in how they are performed; therefore, goal incongruency matters.

Our research in this paper integrates economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior with respect to information processing in the presence of goal incongruency. We develop an information-processing theory of goal incongruency and implement our findings in a discrete event simulation.

Social psychological studies of goal incongruency focus on issues and mechanisms different from those considered in management science. Our model does not claim to shed new light on psychological mechanisms and their effects on behavior, but, rather contributes to the management scientist or manager's understanding of the effects of goal incongruency on organizational performance.

Within the page limits of a single journal article, we cannot satisfactorily both explain VTA's generative mechanisms derived from social scientific theories and present substantive validation of VTA's emergent behavior against empirical date collected on a series of case studies. In a companion paper, "A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations " (Thomsen *et al.*, 1998), we describe in detail VTA's external validation strategy and how we performed the validation on a number of case studies conducted over a three-year period.

In this paper, we apply VTA to a number of small synthetic test cases—"toy" organizations—simple enough models that they could be analyzed manually. Based on "canonical" micro-behaviors of actors (monitoring, selective delegation of authority, exception generation, searching for alternatives, goal clarification, steamrolling, and politicking), we compare the model's emergent behavior according to the predictions of established organizational micro-behavioral theory.

After presenting our point of departure, we review the literature on goal incongruency and other aspects of organizational behavior pertinent to our model. Next, we provide an extensive description of the canonical micro-behavior underlying our computational model and present results from computational synthetic experiments to validate VTA's micro-behavior against the predictions of the underlying organizational theories. The paper concludes with a summary of our practical and theoretical contributions, the limitations of our model, and our suggestions for future work.

2. Point of Departure

Based on models demonstrating that deviation from managerially prescribed goals by subordinates will necessitate additional coordination and communication efforts to resolve the discrepancies (Ouchi, 1979; Eisenhardt, 1985, 1989; Levinthal, 1988; Milgrom and Roberts, 1992), conventional management and economic theories assume that goal incongruency is categorically detrimental to performance. These theories posit that goal incongruency should be unequivocally discouraged.

New data from experiments in social psychology indicate that an intermediate level of goal incongruency may have potentially positive effects on group problem-solving performance (e.g., Amason, 1996; Jehn, 1995; Pelled, 1996; Watson *et al*., 1993; Weick, 1979). On a micro-organizational level, theorists hypothesize that goal incongruency confers two distinct advantages. It forces actors to consider a wider range of possible solutions to a problem, which increases the likelihood that a more ideal solution will be found. We refer to this canonical micro-behavior as "searching for alternatives." Moreover, goal incongruency leads to a greater understanding and clarification of the trade-offs associated with each solution under consideration and encourages actors to formalize their knowledge of these trade-offs implicitly or explicitly into a "goal trade-off table." We refer to this canonical micro-behavior as "goal clarification." Shared goal trade-off beliefs among project participants can be viewed as a common set of values or a shared culture. The existence of shared values or culture is now widely viewed to increase efficiency by serving as a guidepost or touchstone that allows actors to make decisions more quickly and consistently when similar problems arise further downstream (Kunda, 1992).

Boulding (1963) and Pondy (1967) proposed that there exists an optimal level of task goal conflict beyond or below which project team performance diminishes. At high levels, conflict inhibits the abilities of members to gather, integrate, and adequately assess valuable information due to lack of time and wasted effort. At low levels, however, the absence of conflict was shown to hurt group performance by limiting the number and variety of potential solutions considered. This claim has found support from a number of subsequent researchers who have detailed the effects of different levels of conflict. For example, Gersick (1989) discovered that groups exhibiting extremely protracted discussions and a continued lack of consensus were unable to perform any productive work. The members were overly committed to generating alternatives and never progressed to the next step of choosing a solution and implementing it. Janis (1972), however, demonstrated that at less severe levels of conflict, groups performing flexible activities benefited from the diverse ideas of group members. Conflict facilitated the process of critical evaluation, which discouraged “group-think” behavior by promoting thoughtful consideration, constructive criticism, and the generation of alternative solutions. Finally, in environments wherein conflict was completely absent, experiments by Van de Vliert and De Dreu (1994) found evidence that complacency and the lack of any sense of urgency could lead the group to inactivity and to insufficient identification and evaluation of tasks. In addition, research by Schmidt and Kochan (1972) and Gladstein (1984) indicate that increased interaction and interdependence among group members intensify the effect of conflict on group performance.

Organizational demography focuses on variables such as educational background, race, tenure, etc., and assumes that these observable variables affect the goals and, therefore, the behavior and performance of individuals within the organization. Demographic variables affect performance through goal incongruency in our model’s terminology. Research on organizational demography has turned up evidence relating to the potential cognitive benefits of group heterogeneity stemming from the impact of diversity (i.e., Hoffman and Maier, 1961; Nemeth, 1986) and requisite variety (Morrison, 1992; Weick, 1979) on creativity. Nemeth (1986), for example, argues that the quality of reasoning in majority opinions is enhanced by the existence of counter-arguments from a minority. Other researchers have shown that groups are more effective at solving complex, non-routine problems when they are composed of individuals with different perspectives (Shaw, 1976; Wanous and Youtz, 1986). In general, it appears that the presence of diversity in views ensures that problem-solvers will search a larger set of potential solutions, increasing the probability of finding a more optimal solution. Hence, conflict in groups can stimulate effective group discussions, prevent "groupthink," and produce high quality and original decisions (Ghiselli and Lodahl, 1958; Hall, 1982; Hoffman, 1959; Hoffman and Maier, 1961; Janis, 1972; Nemeth, 1985).

The ability of researchers to develop practically applicable insights from the growing body of literature on goal incongruency is retarded by the fact that most experimental data has been generated from studies of dyadic relationships. Experiments involving larger organizations are limited by the inability of the human mind to extrapolate from a single relationship to predictions regarding the emergent effects of goal incongruency in a complex web of relationships. The logistical obstacles to conducting social psychological experiments on large-scale organizations have hindered experiments by organizational researchers, so the conversion of theoretical knowledge about goal incongruency into practical knowledge of how to manage organizations has yet to be accomplished. The dearth of practical insights produced by the research on goal incongruency is further compounded by the lack of research on the relationship between goal incongruency and organizational contingencies, such as the level of interdependence, work process flexibility, and preference for micro-management.

Our research attempts to bridge this gap by providing an analytical tool to help project managers balance organizational design and management policies in such a way that optimum performance is achieved for any given level of goal incongruency.

In the following section, we will first describe theories of organizational goals, organizational members' goals, and how organizational members respond to goal incongruency.

3. Goals in Theories of Organizational Action

3.1 Organizational Goals

Goals are concerned with desired future states of the world, and represent the underlying motives for intentional behavior (Mintzberg, 1983). They are often made explicit and communicated with others in order to coordinate activities and behavior over time. Goals can be understood to characterize present action and to define an attitude towards future conduct. Organizational entities per se are abstractions. They do not possess goals. Rather, it is the dominant organizational group or coalition within an organization that sets the goals or objectives[9] for the organization (Cyert and March, 1992). These objectives can be decomposed into a number of constituent requirements, and each requirement may, in turn, be decomposed again into even smaller requirements. In this manner, carried out iteratively to the lowest level of requirements, a *means-ends hierarchy* of requirements (March and Simon, 1993) can be established in which every requirement constitutes part of the means for achieving the overall objectives.

Typically, the actions, which are undertaken to satisfy one requirement, will affect the likelihood of accomplishing other requirements. Thus, the actions required to satisfy multiple requirements simultaneously may conflict. The task for organizational participants, then, is to find acceptable solutions for achieving a set of interdependent requirements in which the accomplishment of one or more may be detrimental to the fulfillment of others. For example, consider the trade-off between the weight of structural material vs. the level of radiation shielding in a satellite launch vehicle. In some cases, the adoption of an advanced material (e.g., titanium) in one area may result in an undesirable effect in another area. Lightweight structural material provides less radiation shielding than, say, aluminum, thereby requiring the possible addition of more

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[9] A project's outcome can be as diverse as developing a new launch vehicle, designing an innovative automobile, implementing an organizational cost reduction program, setting up an opera, or arranging an athletic event. The outcome is the result of a set of project objectives.

shielding material around sensitive electronic components, which, in turn, offsets some of the weight advantages of the lightweight material.

3.2 Organizational Members' Goals

The project management literature (e.g., Kerzner, 1997) posits cost, duration, and quality as the goals of a project. An actor's best way to serve the project is therefore to focus on the key goals of cost, duration, and quality and *not* on personal goals[10]. This perspective is at odds with the view in utilitarian economics that professionals engage in rational calculation for maximum self-interest (Bonner, 1995). However, Kerzener's view has widespread support in the literature on professions, which holds that professionals broadly suppress the assumption of self-interest in favor of greater emphasis on altruism (Chiles and McMackin, 1996; Ghoshal and Moran, 1996; Nass, 1986).

Cost, duration, and quality are reciprocal constraints, since maximizing one tends to cause a diminishment in one or both of the other variables as long as the organizational slack is at a minimum level (March and Simon, 1993). Because of professionals' local expertise and social embeddedness in the institutional infrastructure of their respective "communities," they will most likely prioritize these goals differently. We refer to the difference in ranking of these three criteria as *goal incongruency* between actors. When actors in an organization favor the adoption of different solutions with which to meet common requirements, we say that a *task conflict* has occurred. Actors' preferences among solutions may differ significantly enough that task conflicts need to be constructively resolved by collaborative negotiation or by hierarchical decision making.

Differences of opinion occur not only between team members in the problem-solving process, but between project 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 in managerial expectations vs. subordinates' aspirations affect the level of

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[10] In addition to a project's requirements, there are a number of overriding project goals that constrain the range of feasible or acceptable potential solution approaches to meet project requirements. Important project goals typically are "completing tasks on time," "staying within budget," and "striving for high task quality." Project goals are differentially impacted by alternative solution approaches. Project participants can have different personal goals and preferences. Thus, they may prioritize project goals differently and hence may favor different solution approaches to meet given requirements.

compliance with the project plan's recommendations. Deviations from the original project plan may give rise to more coordination and communication among members of the project team and can therefore lengthen the total project duration and increase cost.

One area that demonstrates a classic example of goal incongruency is the relationship between the engineers involved with the design and the business-oriented actors responsible for procurement. Traditionally, engineers want to deliver quality specifications and requirements before submitting this information to procurement. Thus, there is a reluctance to provide information early. However, the actors responsible for procurement must procure early enough to deliver the required component on time, and so they want to receive specifications as early as possible.

In introducing actor goals to our model, however, we wish to avoid the complexity of a full-fledged decision-theoretic or utility-based representation (Howard and Matheson, 1983). Models of multi-criteria decision making and collective choice presume that all alternatives for all requirements can be elaborated and ordered with respect to goal functions or utility functions which adopt higher values for better alternatives (Tanguiane, 1990). This turned out to be a practically impossible task on our two case studies (Thomsen *et al*., 1998). Our approach is descriptive rather than normative—we are interested in behavioral changes within the organization in response to goal incongruencies between actors, not in finding the technical solution that optimizes some collective utility function.

The performance of an organization depends on which solutions are chosen and how solutions are supplied to fulfill each of its requirements. Moreover, the selection of these solutions is itself influenced by the goals of individual actors, so goal incongruency is intimately related to organizational performance. The effect of goal incongruency on organizational performance is mediated by a number of other organizational factors. In the following section, we discuss how the characteristics of the activities for which two interdependent, incongruent actors are responsible will determine the extent of conflict between them. A number of other factors, related to the characteristics of the organizational structure and the conflicting actors, determine the local, and emergent global, behavioral responses that are invoked in response to the conflict.

3.3 Goal Incongruency, Task Conflict, and Behavioral Responses

The extent to which goal incongruency will lead to task conflict, and actors' behavioral response, depends on a number of contingency factors. Below, we will describe the major contingency factors that directly mediate the effects of goal incongruency.

Activity flexibility: Brehmer (1976), as well as others (Gladstein, 1984;Van de Ven and Ferry, 1980), suggested that the activity the group performs influences the relationship between conflict and performance. The flexibility of an activity refers to the size of the space of feasible solutions that can satisfy the activity. The more alternatives that exist for fulfilling an activity, the more flexible it is. Given a fixed level of goal incongruency, the effect of that goal incongruency will be less for inflexible activities than in highly flexible ones. The lack of distinct alternatives will reduce the probability that goal incongruency will lead to a conflict of desired alternatives. Even though two parties may have different goals, the limited range of possible choices will mitigate the potential for disagreements over alternatives. In contrast, two incongruent parties are more likely to desire different solutions if the solution space is large, since each party has a greater probability of finding a solution that differentially meets his or her particular preferences. Hence, the effect of goal incongruency increases with the flexibility of the activities being performed.

Activity interdependence: Goal incongruency between two parties will only have a direct effect on actors' behaviors if they are reciprocally interdependent (Thompson, 1967). If the work of one of two parties were completely independent of the work of the other, the actors' incongruent goals would be inconsequential. Thus, high levels of interaction and interdependence intensify the impact of goal incongruency (Gladstein, 1984; Schmidt and Kochan, 1972). A recent study by Jehn (1995) confirmed that conflict had a more profound effect on group performance when members of the group were interdependent. For instance, the problem of goal incongruency is exacerbated in large engineering projects by the sheer complexity of modern engineering artifacts. The need for high levels of interaction among diverse groups (e.g., disciplines, departments, subcontractors) prohibits organizations from simply decomposing tasks and responsibilities and assigning them to strictly delineated departments or groups (Simon, 1996). Consequently, not only must organizations deal effectively with goal incongruency problems arising within supervisor-subordinate relationships but they must also negotiate goal incongruency problems arising in lateral relationships between peers working on interdependent activities.

Disparity in actor competence: Large disparities in the competence levels of interdependent actors will cause an actor who is aware of his or her greater expertise in a certain area to avoid wasting a scarce resource—time—in an extended conflict with a less competent actor. The actor with higher expertise simply appeals to a higher authority (Pfeffer, 1981). We refer to this canonical micro-behavioral process as "steamrolling." Equally competent actors, on the other hand, will be less certain of the superiority of their own solutions and will be more amenable to finding a mutually acceptable solution by means of discussion.

Team experience: The amount of experience that a team has working together can have a profound effect on the behavior of the group. Smith *et al*. (1994) found that team members with a long tenure together will not only have spent more time with one another, which facilitates greater social interaction and cohesion, but they will also have a greater shared understanding of their organization than team members with a shorter tenure. Such teams will be more likely to comprehend the specific idiosyncrasies, strengths, and weaknesses of their organizations. This common basis of understanding accelerates decision-making (Stinchcombe, 1965) and further enhances integration and communication. Ouchi (1980) noted that groups with more experience working together will have a more thorough appreciation of how the organization operates, which promotes team interaction and reduces the need for explicit communication.

Another consequence of team experience is that highly experienced teams are more likely to collaborate with one another in making deals and agreements involving future obligations. Since parties lack direct knowledge of the future behaviors of others, they will rely on past behavior to gain insight into probable future behavior (March, 1995). Hence, within teams whose members have had significant experience working with one another, there will be a higher probability for interdependent actors to attempt to save the scarce resource of time by compromising, and thus avoiding protracted discussions to resolve conflicts (Pfeffer 1981).

The homogeneity vs. heterogeneity of participants in a working group affects performance through goal incongruency. One study by Wagner *et al*. (1984) found that group heterogeneity was correlated with a decrease in interpersonal communication. Observations by Pfeffer (1981) indicate that heterogeneity within groups can give rise to behaviors of a political nature. Drawing on March and Simon (1993, pp. 149-152), we see that such behaviors may include the practice of "politicking," in which one party compromises on one solution in order to elicit another party's compromise on another solution.

Empirical research on construction projects has demonstrated that the apparent dysfunctionality of politicking can, in fact, be highly functional (Kreiner, 1976), particularly in situations in which both parties have the best interests of the organization in mind. Consequently, they can avoid extended communication and negotiation.

Research by Pfeffer (1981) indicates that the phenomena of steamrolling and politicking will not be evident to any significant degree in groups with no goal incongruency. Searching for alternatives or goal clarification, however, will still occur to some extent even in the absence of goal incongruency, since searching for solutions and communicating with interdependent actors are requisite behaviors for performing any activity. As goal incongruency increases, though, all four behaviors will become increasingly manifest. Consequently, the relative proportion of steamrolling and politicking behavior to searching for alternatives and goal clarification will be greater at higher levels of goal incongruency than at lower levels.

Preference for micro-management: Building on Mintzberg's (1973) categorization as well as other theories of leadership, Burton and Obel (1995) demonstrated that leadership styles can be assigned one of two categories based on how managers process information and make decisions. The difference between the two categories is rooted in whether or not a manager has a preference for micro-management (i.e., the habit of becoming heavily involved in the day-to-day affairs and activities of subordinates). The effect of goal incongruency on vertical relationships either will be magnified or mitigated, depending on the leadership style of the manager involved. "Micro-managers" will react more strongly to goal incongruency with their subordinates than non-micro-managers. Such managers, for example, will engage in greater "monitoring" and are likely to appropriate decision-making power away from the subordinate, i.e., micro-managers "selectively delegate authority."

In the following section, we describe how we interpreted and implemented these behavioral responses to goal incongruency in an information-processing framework of organizations.

4. The Virtual Team Alliance (VTA) Computational Model of Project Teams

Following Galbraith (1973, 1977), researchers at Stanford University created the Virtual Design Team organization simulation framework (Christiansen, 1993; Cohen 1992; Jin and Levitt, 1996). 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). In sections 2 and 3, we identified canonical micro-interaction processes between actors. Since we want to use VDT as the basis for our organizational simulation framework, we need to represent these canonical micro-behavioral processes as extensions of VDT's two communication and decision-making processes.

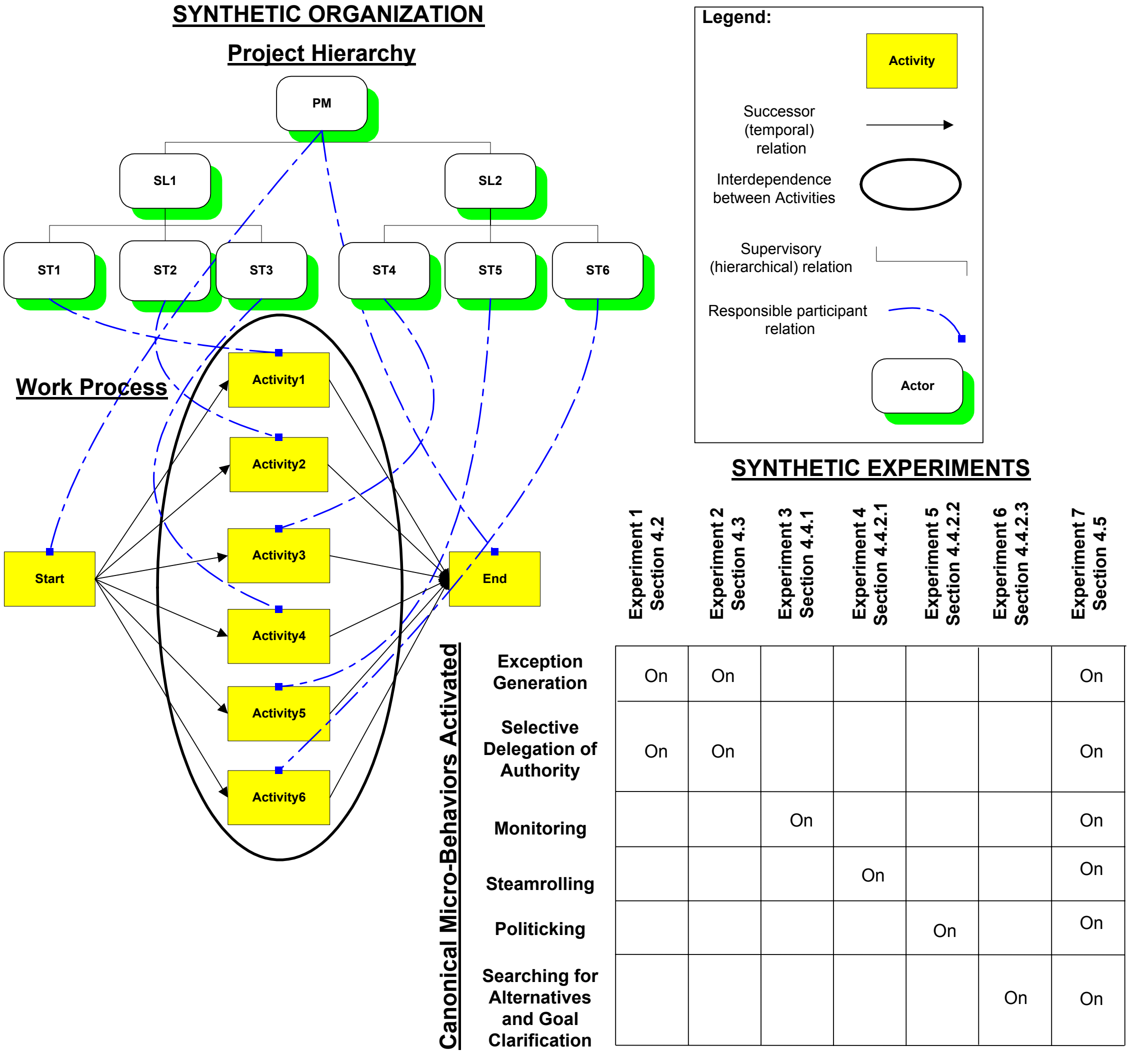
4.1 Overall Model

In project teams, the manager has typically created a Critical Path (CPM) Model of the work process. Actors fill a position in the organizational hierarchy and are assigned to activities in the CPM. Some actors may not have any direct responsibility for activities, but only for managerial responsibilities. An activity is divided into sub-activities or work packages. There are many potential ways of performing the sub-activities (measured by flexibility). These sub-activities are the drivers of action in our model. Any time that the information available to the responsible actor is less than the information needed to execute the sub-activity, an exception is generated (Galbraith, 1973). We introduce an additional kind of exception, wherein the actor has more expertise or information than required to perform the sub-activity in the standard or expected manner. The probability of exception generation depends on the attributes of the activity (and therefore the sub-activity), activity complexity, activity flexibility, skill requirement, and interdependence strength between activities as well as an actor's attributes—goal priorities and skills.

Moreover, the responsible actor may decide that it will engage in either hierarchical or peer-to-peer communication after completion of each sub-activity. The probability of generating a communication also depends on the attributes of the actor (goal priorities, preference for micro-management) and activities (activity uncertainty, activity flexibility, and interdependence strength).

The CPM model and organizational hierarchy constrain actors' opportunities for action. The assignment of requirements to activities and activities to actors choreograph the interaction between actors. A key assumption is that the technical engineering content of activity requirements does not vary in relation to changes in organizational design. Pairs of project activities contribute to different requirements; that is, they are independent of one another. Other pairs of project activities contribute to the same requirements; that is, they are interdependent with one another. If two activities that are interdependent are executed concurrently, there will be a need for problem solving by their responsible actors to come up with a mutually satisfactory solution that meets their shared requirements. If two activities that are interdependent are executed sequentially, there is a probability that the first activity will be restarted to account for potential failures in the second activity. Not all activities are equally interdependent; activities are more or less interdependent depending on the number of shared requirements.

In section 4.2, 4.3, 4.4, and 4.5 we describe in detail how VTA actors comprise a complex system that is endowed with fragments of canonical information-processing micro-behavior. We apply VTA to the "synthetic organization" illustrated in Figure 1. We perform seven synthetic experiments to validate VTA's seven canonical interaction micro-behaviors (exception generation, selective delegation of authority, monitoring, steamrolling, politicking, searching for alternatives and goal clarification) internally by activating one at time (Figure 1).



Canonical Micro-Behaviors Activated	Experiment 1 Section 4.2	Experiment 2 Section 4.3	Experiment 3 Section 4.4.1	Experiment 4 Section 4.4.2.1	Experiment 5 Section 4.4.2.2	Experiment 6 Section 4.4.2.3	Experiment 7 Section 4.5
Exception Generation	On	On					On
Selective Delegation of Authority	On	On					On
Monitoring			On				On
Steamrolling				On			On
Politicking					On		On
Searching for Alternatives and Goal Clarification						On	On

Figure 1: **An Overview of the Synthetic Organization and the Synthetic Experiments we used for Internal Validation.** The upper left part of the figure shows the work process and the project hierarchy of the synthetic organization. In our conceptual model, a project includes actors (rounded rectangles) and the activities (rectangles)—that are interrelated. That is, each project participant fills a position in the project organizational hierarchy and works on one or more activities. The table in the lower right part of the figure shows the VTA canonical micro-behaviors in response to goal incongruency, in which experiments they are internally validated, and the subsection in which the experiment is discussed.

4.2 Exception Generation

As each sub-activity is executed by the simulator, the goal-oriented subordinate responsible for activity may generate exceptions to the project plan since it is boundedly rational (Simon, 1956). Exceptions are one of two types—technical errors (TE) and non-conformances (NC). Technical errors are errors arising from a technical oversight, technical incompetence, or any number of mistakes that might have been avoided had the subordinate been more circumspect or technically proficient. Non-conformances are exceptions that arise directly from goal incongruencies between the manager and the subordinate. They are not incorrect from a technical standpoint (i.e., the final product will not be defective if the non-conformance is not remediated); rather, they do not conform to the approach that the manager had prescribed or desired.

The chance that a technical error will be generated is based on the complexity of the activity as well as the actor-activity skill match. Figure 2 shows that the chance that a subordinate will generate a non-conformance is based on the level of goal incongruency between the supervisor and the subordinate and the activity flexibility. If the exception is a non-conformance, its probability of being a productive non-conformance (PNC) is determined by consideration of the difference in skill between the subordinate and the supervisor. A relatively unskilled supervisor will encounter more productive NCs from a highly skilled subordinate than *vice versa*.

The exception is forwarded to the appropriate supervisor who decides how to deal with the exception. In the cases of TE and counterproductive non-conformances, such decisions involve reworking portions of the activity that failed. In the case of PNCs, such decisions involve reducing portions of the primary work volume of the activity in which the PNC was generated. Ignoring/rejecting an exception is acceptable as long as the decision-maker has made an evaluation of the consequences of the decision. However, as soon as the decision-maker becomes overloaded, it may not have a chance to detect the exception or get to the decision. In this case, the actor waiting for the decision proceeds by "default delegation."

If a large number of technical errors or non-conformances are undetected or not attended to, decision-making quality will tend to suffer. Correction and reworking of technical errors and accepting and modifying counterproductive non-conformances will increase decision-making quality, but at the immediate expense of cost and time. In contrast to the negative effects of technical errors and counterproductive non-conformances, productive non-conformances will allow the project to terminate more quickly and efficiently, given that they are not eliminated through rejection (i.e., a productive non-conformance can only be beneficial if the non-conformance is accepted and allowed to stand).

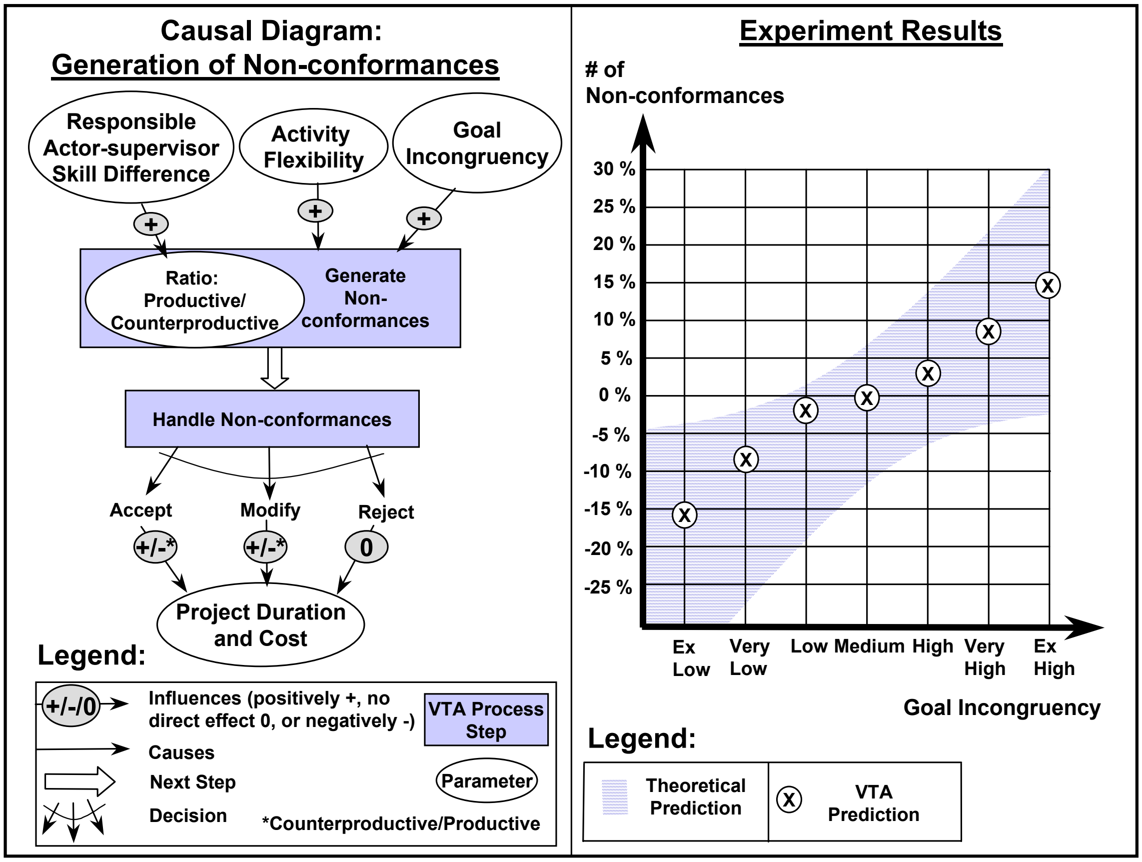


Figure 2: **Generation of Non-conformances.** The effect of responsible actor-supervisor skill difference, activity flexibility, and goal incongruency on the generation of non-conformances (NC). Activity flexibility and goal incongruency between the supervisor and subordinate determine whether a NC is 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. Only the exception generation and selective delegation of authority micro-behavioral processes were activated. Simulation results agree qualitatively with organizational contingency theory and they are stable.

4.3 Selective Delegation of Authority

Selective authority delegation refers to the process by which managers determine how much decision-making power to grant to subordinates. High goal incongruency levels will lead managers to demand that a greater proportion of exceptions be reported to them for decision making, while low goal incongruency levels will encourage managers to allow subordinates to handle exceptions on their own. Low levels of authority delegation will, in turn, effectively increase the level of centralization in regard to local decision-making within the organization and provide managers with greater control over the workflow.

As a rule, the perception of high levels of goal incongruency, as well as a propensity for micro-involvement on the part of the manager, will cause a manager to delegate less authority to subordinates (Burton and Obel, 1995) (Figure 3).

Based on Simon's (1997) theory that the cognitive limitations of human actors will cause them to be more likely to identify with the goals for which they are most directly responsible, higher-level actors are assumed to be motivated by project-level goals rather than requirements for activities. By virtue of their global perspective on the project, managers have a greater awareness of the ramifications that a failure in one activity could have for other interdependent activities. Hence, higher-level actors in our model tend to decide to perform rework, rather than to "quick-fix" or ignore the error when errors are detected, and *vice versa*[11].

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[11] Note: This cultural assumption that higher level engineering managers are more likely than their subordinates to rework all errors had to be flipped when we modeled a software development team. In this case the programmers wanted to fix all bugs, whereas the project manager was willing to ship the software with known, non-serious bugs to meet the promised release date.

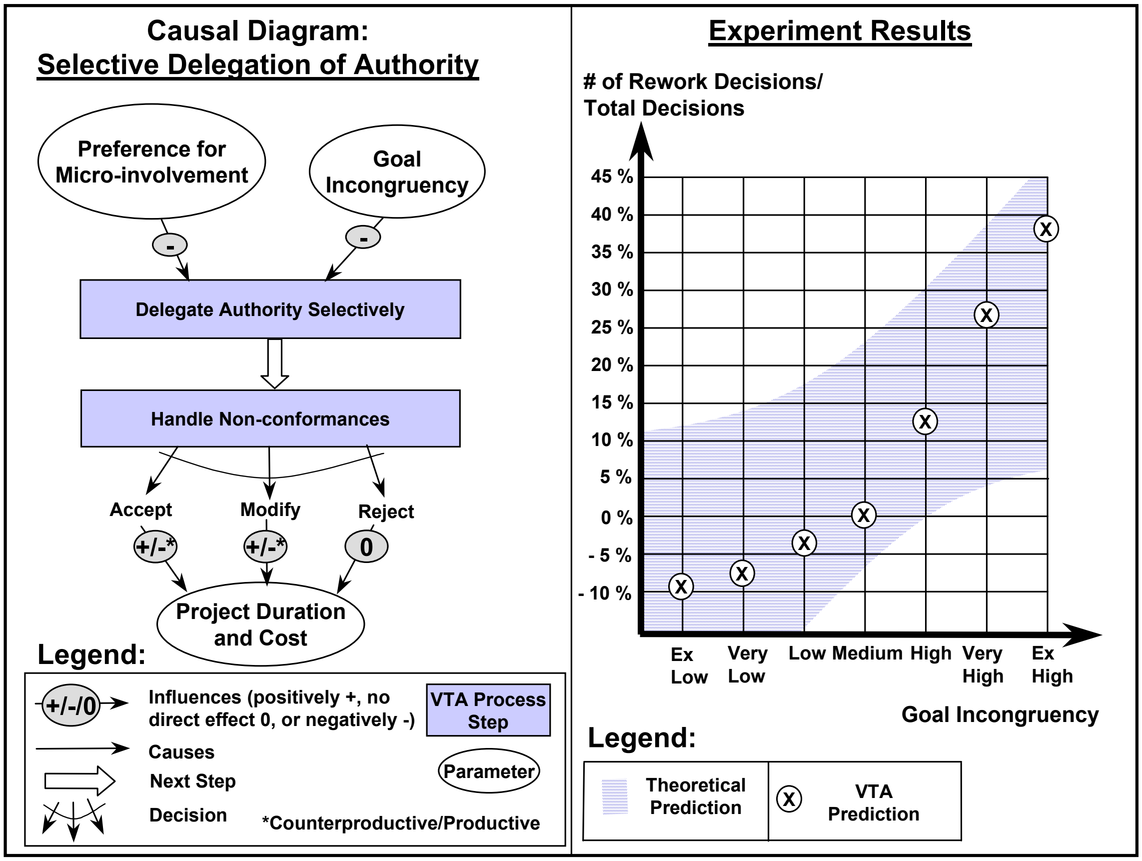

Figure 3: **Selective Delegation of Authority.** Preference for micro-involvement and goal incongruency determine the distribution of authority in each vertical chain of command. The right part of the figure shows the results from our simulation analysis. Only the exception generation and selective delegation of authority micro-behavioral processes were activated. Simulation results agree qualitatively with organizational contingency theory and they are stable.

4.4 Information Exchange

In this section, we describe a total of five well-validated canonical interaction micro-behavioral processes in response to goal incongruency: one for vertical relationships and four for lateral relationships. Each response is not necessarily exclusive of the others, and the extent to which each one is invoked is contingent on the level of goal incongruency as well as other organizational factors.

4.4.1 Monitoring

Given that our model is based on an information-processing view of organizations, we represent all managerial control mechanisms through the processes of monitoring and the aforementioned selective authority delegation (Eisenhardt, 1989). Our model calculates the level of monitoring and delegated authority for each hierarchical dyad relationship by first considering the overall level of monitoring and the degree to which decision-making is centralized and then by locally modifying these initial values for each dyad relationship. This modification is based on the characteristics of individual actors—i.e., the manager's preference for micro-involvement (Burton and Obel, 1995)—as well as the level of goal incongruency within each relationship.

Monitoring in our model incorporates all the specific activities involved in the use of control mechanisms, including the transmission of information concerning behavioral observations, evaluations, and prescriptions. It is a cyclic process in which managers periodically administer new prescriptions to subordinates and request progress reports on the status of work packages. Subordinates, in turn, send reports and questions up to supervisors. The number of managerial prescriptions that are issued will affect how much latitude subordinates have in terms of deviating from managerial expectations. As more prescriptions are sent down the hierarchy and attended to by subordinates, the probability that a subordinate will generate an exception will decrease. When subordinates do not attend to managerial prescriptions, however, the probability that they generate an exception will increase rather than decrease, since the subordinate will not be aware of the new prescription and may inadvertently deviate from it. In a similar vein, as more reports and questions are channeled up the hierarchy by subordinates and attended to by managers, managers will become more aware of the status of work packages. Attended-to-reports will result in a greater probability that exceptions will be detected. However, when managers are overworked and do not attend to reports, the probability of exception detection will decrease.

As a rule, the perception of high levels of goal incongruency, as well as a propensity for micro-involvement on the part of the manager, will cause a manager to engage in more extensive monitoring, while perceived concurrence will result in a lessening of the intensity of monitoring.

Figure 4 illustrates how we have implemented monitoring. At the completion of each sub-activity, the subordinate might send a report to the supervisor based on the goal incongruency between the subordinate and supervisor as well as on the supervisor's preference for micro-management. The supervisor may or may not attend to the report based on the supervisor's current backlog. If the supervisor attends to the report, the supervisor will reply to the subordinate, whose likelihood for attending to the reply is based on its own attention allocation. Moreover, each time that a manager attends to a report from a subordinate, the manager might send a message up to its supervisor based on the goal incongruency between itself and the next-level supervisor as well as on the supervisor's preference for micro-management. Attending to reports increases the probability that exceptions will be detected. Thus, monitoring requires time on the part of the supervisors and subordinates. Monitoring items must be initiated, attended to, and responded to. However, monitoring generally leads to an increase in decision-making quality, since more exceptions are detected and handled properly. On the other hand, this increase may be offset by a decrease in coordination quality if the hierarchy becomes overloaded with monitoring communications. It is clear that there will be some optimal level of monitoring—too little may result in an excess of exceptions as a consequence of goal incongruency, and too much may overload actors to the point that they become seriously backlogged. Amount of monitoring is especially a concern for supervisors with a large span of control.

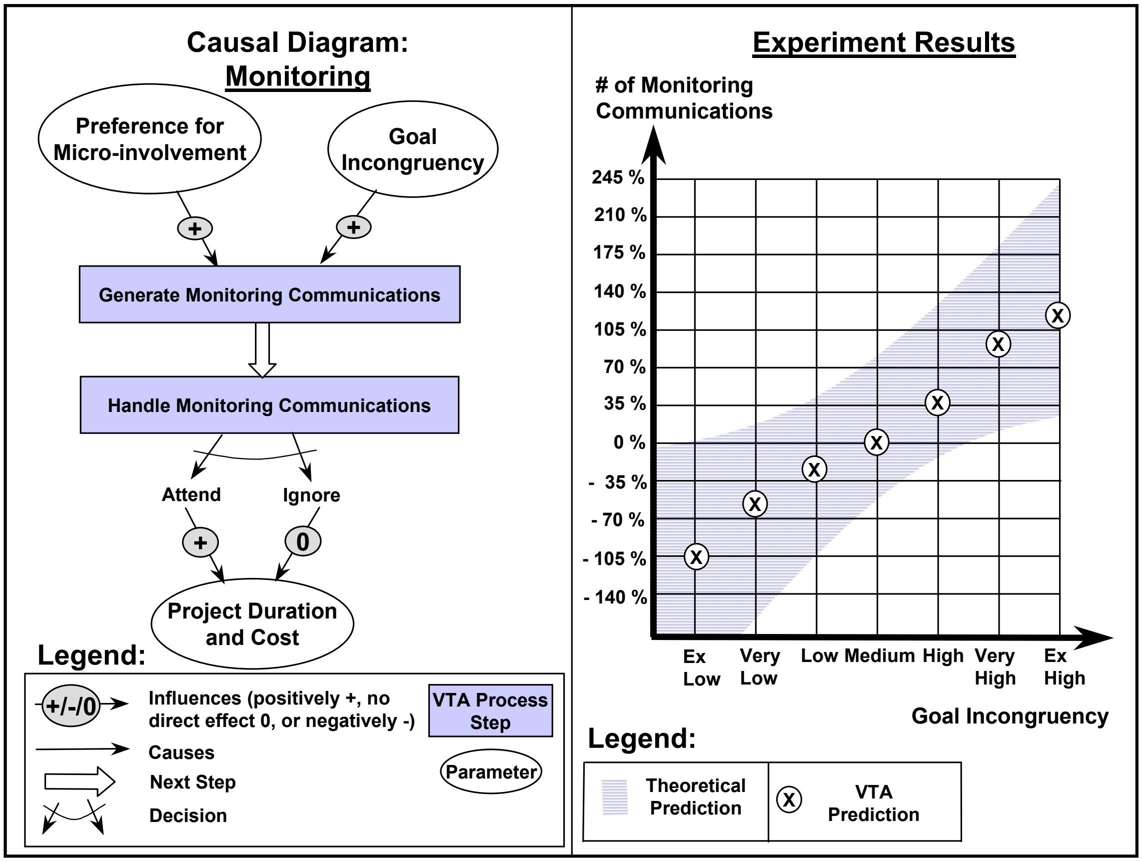

Figure 4: **Monitoring.** Preference for micro-involvement and goal incongruency determines the level of monitoring in each vertical dyad. The right part of the figure shows the results from our simulation analysis. Only the monitoring micro-behavioral processes were activated. Simulation results agree qualitatively with organizational contingency theory and they are stable.

4.4.2 Peer Communication

A comprehensive model of organizational behavior needs to consider the lateral interaction among project members, as well as the interactions between managers and subordinates. In section 2 and 3, we identified four responses that peer actors can make in reacting to goal incongruency—steamrolling, politicking, searching for alternatives, and clarification of goals.

4.4.2.1 Steamrolling

Steamrolling is a process in which one actor appeals to a higher authority to force some other actor to perform an action. In our model, steamrolling occurs only within interdependent relationships and is most prevalent in relationships with high goal incongruency. In an interdependent relationship, there is a probability that one actor will appeal to the supervisor through an external counterproductive non-conformance exception (i.e., an exception that affects an activity other than the one in which it was generated) to force an interdependent actor to perform additional work. This probability increases with the level of goal incongruency between the two interdependent actors, to reflect the greater propensity for steamrolling in disharmonious relationships. If the manager agrees with the subordinate (i.e., if there is a low level of goal incongruency between the subordinate and his or her manager), then the actor that is the victim of the steamrolling will be forced to undertake additional work. In addition, the disparity in competence between interdependent actors affects the likelihood of steamrolling. Their skill levels and the amount of experience they have had performing activities similar to the current one are the yardstick by which competence is measured. If the disparity is large and one actor is more competent than the other, the more competent actor will have greater confidence in the merit of its own solution. The more competent actor will be less inclined to spend time working with the less competent actor to find another solution or to examine carefully the advantages and disadvantages of each proposed solution. Rather, it will be more likely to try to save time by simply steamrolling the other actor to facilitate quick acceptance of its solution (Figure 5). In contrast, if the disparity in actor competencies is small, the actors are more likely to engage in searching for additional solutions and in clarifying goals in order to arrive at a satisfactory decision. Also, each actor is more likely to give greater weight to the opinions of the other and will be less certain that his or her own solution is categorically better than the other's.

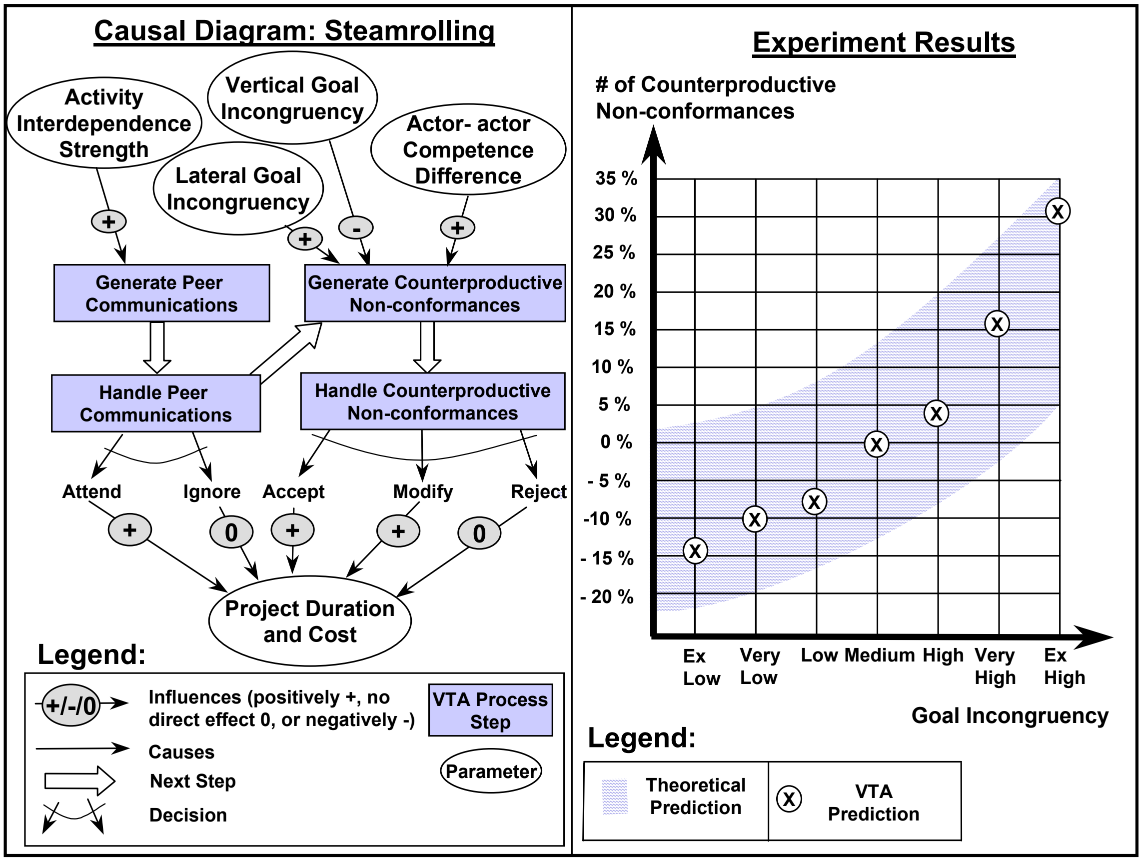

Figure 5: **Steamrolling.** The left part of the figure shows how we implemented steamrolling behavior in VTA. The right part of the figure shows the results from our simulation analysis. In this test case only the steamrolling micro-behavioral processes were activated. Simulation results agree qualitatively with organizational contingency theory and they are stable.

4.4.2.2 Politicking

Politicking is the process by which one actor persuades another interdependent actor to accept its solution in return for a promise to accept the other's solution in the future. Politicking can occur only when social exchange processes come into play, i.e., when actors expect to interact with one another repeatedly over extended periods of time, exchanging favors and obligations. Hence, the degree to which politicking processes are expected to take place in a project team depends on the amount of time that the members of the team have been working together (in our model, given by the "team experience" variable). A long history of association and collaboration is necessary for actors to trust one another to return favors.

Team experience lessens the need for explicit coordination between actors because they have learned to anticipate one another's needs or demands and can coordinate more tacitly. The benefits of high team experience will be greatest when there are low levels of goal incongruency between actors. As goal incongruency increases within highly experienced teams, though, members will begin to resort to alternative means of resolving differences in order to get things done and to avoid being stalemated indefinitely in time-consuming arguments. Politicking will become more apparent, and although it will reduce the volume of communication produced by the higher levels of goal incongruency, it will occur at the expense of finding better solutions. Hence, high team experience combined with high goal incongruency will increase the probability of counterproductive non-conformances being generated in addition to reducing the probability of peer communications being generated. For a given level of team experience, the number of peer communications will decrease and the number of counterproductive non-conformances will increase for higher levels of goal incongruency (Figure 6).

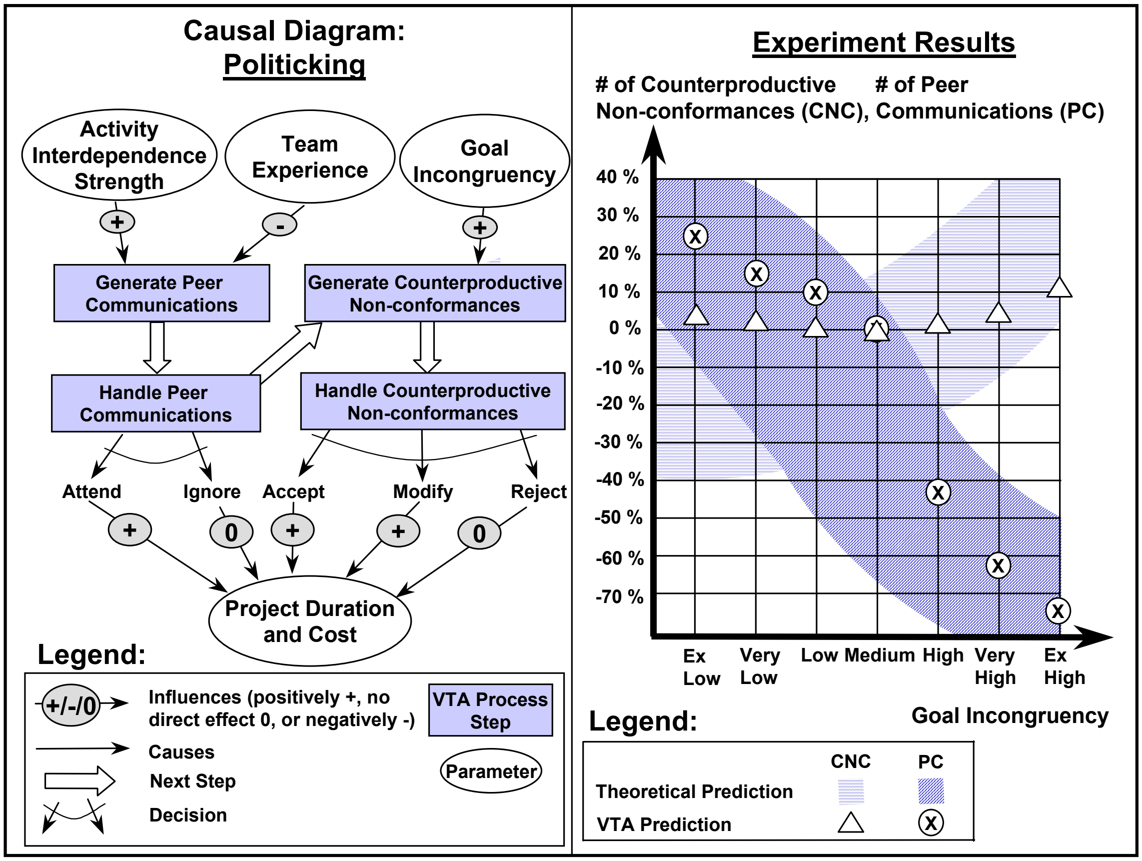

***Figure 6:* Politicking.** The left part of the figure shows how we implemented politicking behavior in VTA. The right part of the figure shows the results from our simulation analysis. In this test case, only the politicking micro-behavioral processes were activated. Simulation results for both counterproductive non-conformances and peer communications agree qualitatively with organizational contingency theory and they are stable.

4.4.2.3 Searching for Alternatives and Goal Clarification

In our model, the processes of searching for alternatives and goal clarification are considered to have the same effect on organizational behavior. Searching for alternatives necessitates increased communication between actors working on interdependent activities as they collaborate with one another in generating new solutions and seek to reconcile their differences to arrive at a solution which is mutually acceptable. Goal clarification likewise increases the volumes of communications as actors attempt to develop some sense of the costs and benefits associated with each solution. Hence, in an information-processing framework in which the content of activities is abstracted from the model, the effects of these two processes are the same.

Goal incongruency will force actors to consider a wider range of possible alternatives in order to find a mutually acceptable solution to the problems at hand. The more alternatives that are evaluated the higher the likelihood that a more ideal solution will be found. Goal incongruency will lead to a greater understanding and clarification of trade-offs associated with the solutions under consideration. The immediate effect of searching for alternatives and goal clarification in our model is to increase the volume of communication (Figure 7). When communications are well attended to, the number productive non-conformance will increase because of the gain in time afforded by more efficient decision-making and the increased likelihood that the collaborating actors will derive a more globally productive solution. However, at very high level of goal incongruency the number of productive non-conformances will decrease because the interdependent actors are less likely to find mutually productive solutions (Figure 7). The increase in peer communications and the upside-down u-shaped effect on number of productive non-conformances is commensurate with the flexibility of the activities in question. Greater activity flexibility means that there is a broader space of alternatives that must be searched through, and more goals to clarify, while lower activity flexibility indicates that there is a smaller solution space and fewer goals need to be considered. The effects of goal incongruency on peer communications and productive non-conformances are intensified for higher levels of activity flexibility.

The effect of the increase in communication volume depends on how well those communications are attended to. When communications aimed at resolving goal incongruency by searching for alternatives or clarifying goals are not attended to by the recipient actor, actors will be more likely to select alternatives that are not mutually satisfying. The process of developing a shared view of goal trade-offs will be interrupted.

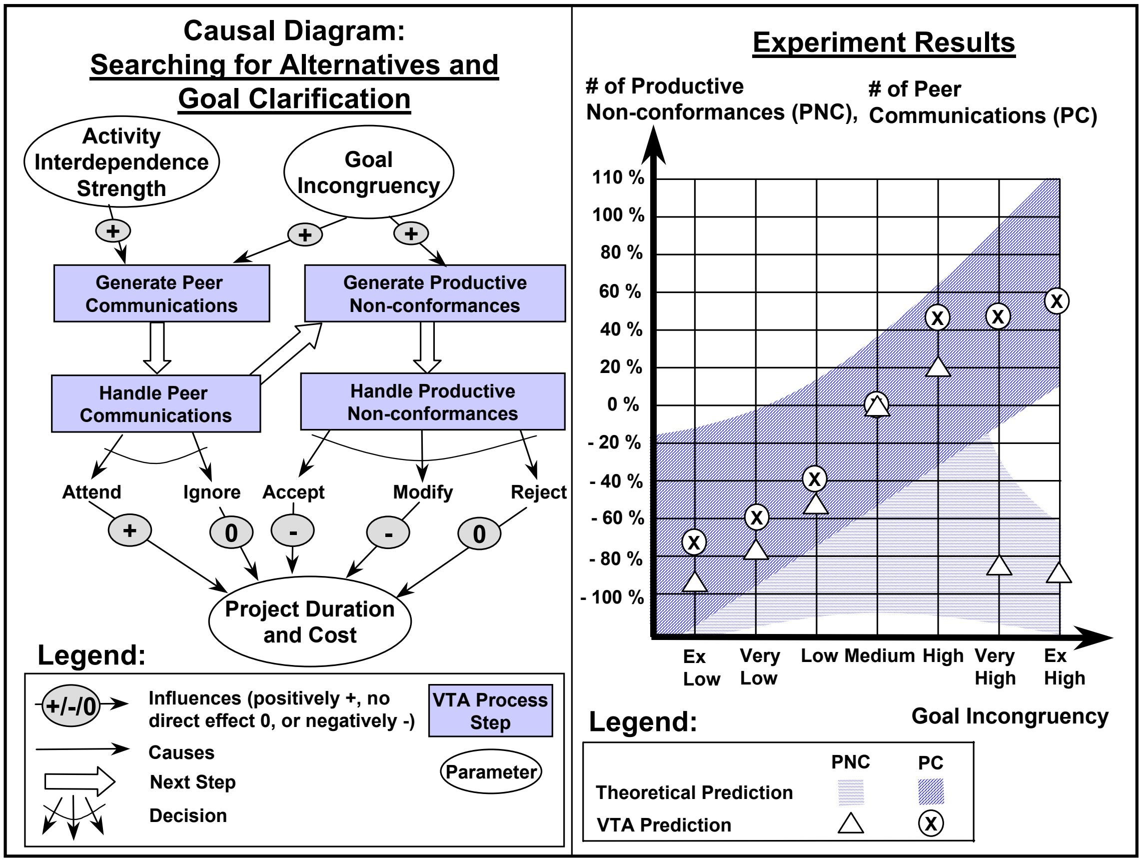

Figure 7: **Searching for Alternatives and Goal Clarification.** The left part of the figure illustrates how we implemented the "searching for alternatives and goal clarification" behavior in VTA. The right part of the figure shows the results from our simulation analysis. In this test case only the searching for alternatives and goal clarification micro-behavioral processes were activated. Simulation results agree qualitatively with organizational contingency theory and they are stable.

4.5 The Emergent Macro-behavior of VTA

We have presented our model for investigating the emergent effects of goal incongruencies between individual or group actors on project team performance. To determine the usefulness of this model, we need extensive external validation. Our companion paper, "A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations," discusses results of the experiments that were conducted to validate the VTA model on real-world project organizations.

However, we want to illustrate how we validated VTA's emergent macro-behavior internally according to the predictions of established organizational macro-theory. To summarize our discussion in sections 2 and 3, 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. It can, therefore, improve the project performance, e.g., reduce project cost and duration (Weick, 1979). At the same time, organization theory indicates that too much goal incongruency can lead to time-consuming arguments, thus undermining project performance, e.g., increasing project cost and duration (March and Simon, 1993). Hence, organization theory predicts a curvilinear u-shaped relationship between goal incongruency and project cost and duration (Figure 8).

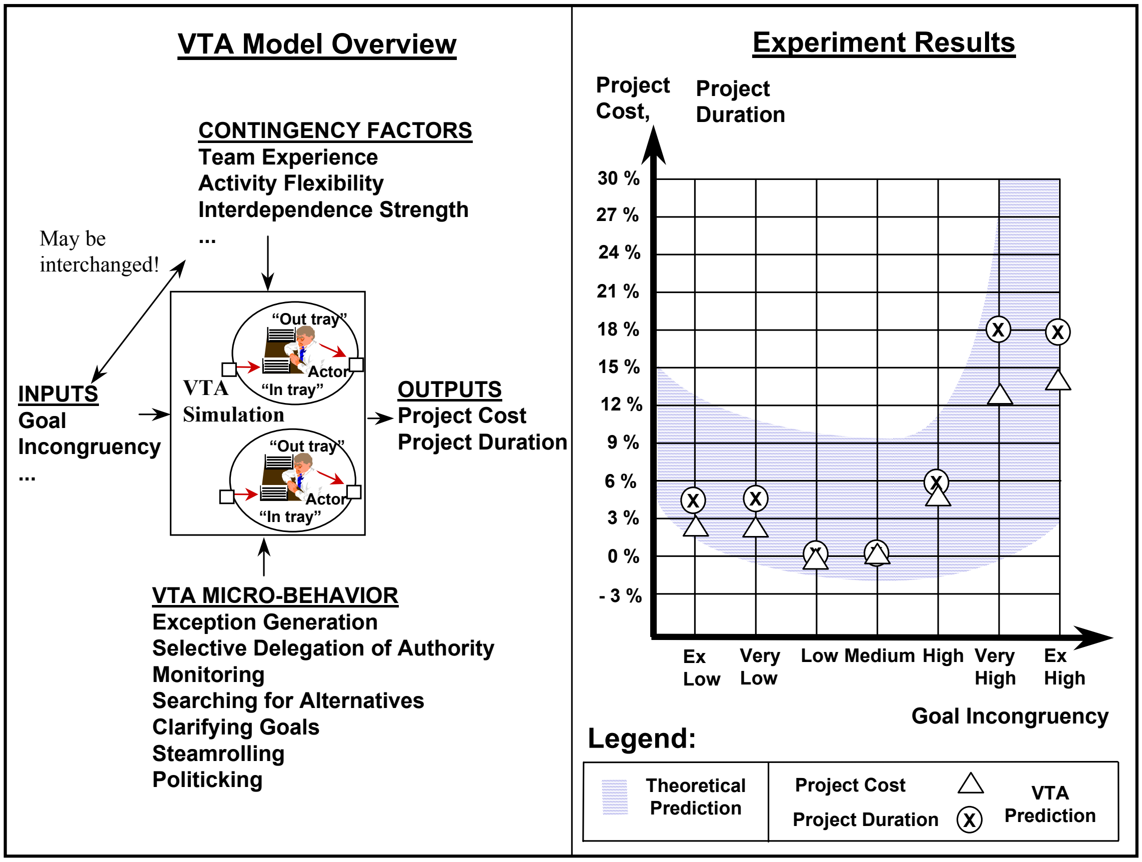

Figure 8: **An Overview of the VTA Model and Emergent Simulation Results.** The right part of the figure shows the results from a simple experiment on the same synthetic organization that we used in the experiments above. In this experiment, all seven micro-behavior processes were activated. Simulation results agree qualitatively with organizational theory and are stable, with a coefficient of variation (CV) between 1 and 5 percent for all settings.

5. Discussion

Semi-routine, fast-paced projects with interdependent and concurrent activities and professional project participants from multiple organizations create unique management challenges. Computational organizational modeling affords us with opportunities to both understand and respond to these complex challenges.

Relying on our actor and work process assumptions, we focused on augmenting the information-processing behavior within the VDT discrete-event simulator framework by adding behaviors related to actors with incongruent goals executing activities with some flexibility. We then performed synthetic experiments to illustrate and validate each of the canonical micro-behaviors of our extended computational model and their combined effects on emergent project performance. We found that our information-processing operationalization of exception generation, monitoring, selective delegation of authority, searching for alternatives, clarifying goals, steamrolling, and politicking agreed qualitatively with the micro-theoretical predictions. We validated the model's emergent macro-behavior according to the predictions of established organizational macro-theory, and found qualitative consistency here as well. Our micro-contingency model extends information-processing organization theory by introducing and operationalizing the effects of contingency factors such as activity flexibility, interdependence between activities, etc. External validation discussed in a companion paper (Thomsen *et al.*, 1998) introduces new findings and suggests a new set of contingent propositions about the effects of goal incongruency on organizational performance.

5.1 Contributions

The dominant approach for studying performance in multi-constituency project teams has been grounded in the transaction-cost framework (Williamson, 1979). This theory focuses on the relationship among consumers and suppliers and the contracts, which regulate their transactions. In this paper, we have chosen to focus on the constituents of a project team. By simulating actors executing micro-behavior interactions, VTA generates emergent system-level behavior that advances the science and “engineering” of semi-routine, fast-paced project organizations.

Relying on organizational theories developed in the 1970s when speed and flexibility were less relevant for organizational success than they presently are for firms, organizational simulations have been used in the organizational sciences to improve the design of real-world projects that perform *idealized, routine* work processes. We relax these limiting assumptions, and combine field insights with economic agency theory and sociological and social psychological theories of organizational design to describe rich repertoires of canonical micro-behavior in real-world, fast-paced product development projects. In the VTA model, actors are endowed with fragments of canonical micro-behavior, and then assembled into networks of activities and actors to represent real-world activities and organizations.

The less routine nature of fast-paced work processes means that decision making requires *judgment* (Thompson and Tuden, 1959) and *interpretation* (Pava, 1983) by the professionals who carry it out. We therefore represent project participants, actors, as teleological professionals with potentially incongruent goals. In addition, our work process representation captures the fact that less routine work includes flexibility that may result in more complex exceptions than the sort characterized by Galbraith (1977).

In developing the conceptual extensions for VTA, we have extended existing contingency theory (Thompson, 1967) and Galbraith's information-processing theory (Galbraith, 1973, 1977). We claim that these extensions create a new theoretical basis for our model of semi-routine, fast-paced projects consisting of professionals from multiple disciplines. Galbraith and other contingency theorists focus on organizational behavior at the level of the organization itself, and do not concern themselves with the internal dynamics of the organization. Goal incongruency, however, surfaces in the dyadic relationships between individual actors, and it is only at this level that one can apply the findings garnered from economic agency theory and social psychology about the potentially positive as well as negative effects of goal incongruency. Given our need to create a model for goal incongruency that considers its local influence on the internal micro-behavior of individual actors within organizations, we have extended contingency theory to develop a micro-contingency model of goal incongruency and organizational behavior. Our VTA model takes the relationship between pairs of actors as the fundamental unit of analysis.

Within the larger framework provided by Galbraith's information-processing model, we incorporate and operationalize behavioral and organizational theories, which analyze goal incongruency behavior at the level of individual actors and relationships. These theories cover the behavior of actors embedded in vertical dyadic relationships in the organizational hierarchy, as well as the behavior of peer actors working on interdependent activities. We depict organizational actors as relatively simple, goal-oriented, information processors and communicators with finite or "boundedly rational" capacity (March and Simon, 1993). Their work is choreographed by

- relatively abstract, flexible, sequentially and reciprocally interdependent information-processing activities assigned to them (Thompson, 1967), and
- organizational structures that reactively handle exceptions from pre-planned activities in the spirit of Galbraith (1973, 1977) and proactively monitor the behavior of subordinates (Ouchi, 1979; Eisenhardt, 1985).

The past VDT work operationalized aspects of Galbraith's information-processing view of organizations. VTA extends Galbraith's framework to address less routine activities with some flexibility in how they are performed. Since activities are now flexible, differences in goals may influence which solutions project participants prefer, so that goal incongruency matters. VTA integrates economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior with respect to information processing in the presence of goal incongruency. To Galbraith's sociological analysis, based on "organizational physics," we add new social psychological and economic agency notions of "organizational chemistry."

5.2 Limitations and Future Work

To be amenable to analysis in our framework, a semi-routine, fast-paced project should first have relatively clear objectives. Second, project managers should understand work processes well enough so they can relate requirements to processes and assign pre-specified activities to different, specialized individuals. Third, the interactions among project participants responsible for activities must be derivable from requirements. Fourth, we model exceptions to pre-specified activities by adding or subtracting work to these activities. While these assumptions do not apply to all projects or organizations, they apply well to many engineering design and product-development activities as well as organizations that are moving to organize their ongoing work processes as "projects" (Hammer and Champy, 1993; Davidow and Malone, 1992).

Our model is not applicable to contingent work processes, such as those often found in engineering maintenance and medical service activities. Diagnostic and repair activities are by their nature conditional. Depending on the results of the diagnosis, completely different repair strategies should be used. To simulate the way an organization would perform these activities within a particular setting, we would have to develop an enriched set of micro-behavior to model the conditional aspects of these activities and to determine new product and process quality evaluation metrics (Fridsma and Thomsen, 1997).

Procurement presents a classical organizational goal dilemma: an engineer may want to hold on to a design to improve its quality, but schedule pressures encourage releasing the design to procurement as early as possible. In the traditional aerospace industry procurement model, manufacturing could accommodate design changes relatively easily when design and manufacturing were done by the same organization. With manufacturing by outside contractors becoming more frequent, engineering change orders often become more formal, expensive and time-consuming. The agile organization creates greater tension regarding time-quality trade-offs. We can represent such tensions through goal incongruency between project participants. However, in our model, goal incongruency is static. That is, there is no change in goal incongruencies over the course of the project. Such a view of goal incongruency, however, is at odds with actual behavior, since people adopt different goals over time. For example, engineering professionals customarily prefer to attend to activities "on the critical path;" and the critical path can change several times during a project. A more detailed model of goal incongruency would account for learning and adaptation by individuals and view goal incongruencies as dynamic variables. The fundamental tenet of goal-driven learning is that learning is largely an active and strategic process. The learner attempts to identify and satisfy its information needs in the context of its activities and goals, its prior knowledge, its capabilities, and environmental opportunities for learning. We would need to add to the simulator dynamic goal modification methods that allow actors to adjust their goals during a simulation, based on factors such as activity status on the critical path or changing estimates of activity risk.

6. Acknowledgments

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7. References Cited

Amason, A., (1996), “Distinguishing the effects of functional and dysfunctional conflict on strategic decision making: Resolving a paradox for top management teams,” *Academy of Management Journal*, 39, 123-148.

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.

Boulding, K. (1963), *Conflict and Defense*. New York: Harper and Row.

Brehmer, B. (1976), “Social Judgment theory and the analysis of interpersonal conflict,” *Psychological Bulletin*, 83, 985-1003.

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

Burton, R. M. and B. Obel (1995), *Strategic Organization Diagnosis and Design: Developing Theory for Application*. Norwell, MA: Kluwer Academic Publishers.

Carley, K. M. and Z. Lin (1995), "Organizational Designs Suited to High Performance Under Stress," *IEEE Transactions on Systems, Man, and Cybernetics*, 25(2), 221-230.

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.

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.

Eisenhardt, K. M. (1985), “Control: Organizational and Economic Approaches,” *Management Science*, 2, 134-149.

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

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. R. (1973), *Designing Complex Organizations*. Reading, MA: Addison-Wesley.

Galbraith, J. R. (1977), *Organization Design*. Reading, MA: Addison-Wesley.

Gersick, C. J. G. (1989), "Marking time: Predicable transitions in task groups," *Academy of Management Journal*, 32, 274-309.

Ghiselli, E. E and T. Lodahl (1958), "Patterns of managerial traits and group effectiveness," *Journal of Abnormal and Social Psychology*, 57, 61-66.

Gladstein, D. L. (1984), "A model of task group effectiveness*," Administrative Science Quarterly*, 29, 499-517.

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

Hall, R. H. (1982), *Organizations: Structure and Process*. Englewood Cliffs, NJ: Prentice Hall.

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

Hoffman, L. R. (1959), "Homogeneity of member personality and its effect on group problem solving," *Journal of Abnormal and Social Psychology*, 58, 27-32.

Hoffman, L. R. and N. R. F. Maier (1961), "Quality and acceptance of problem solutions by members of homogeneous and heterogeneous groups*," Journal of Abnormal and Social Psychology*, 62, 401-407.

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.

Janis, I. (1972), *Victims of Groupthink*. Boston, MA: Houghton Mifflin.

Jehn, K. (1995), "A multimethod examination of the benefits and detriments of intragroup conflict," *American Journal of Sociology*, 82, 929-964.

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

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

Kreiner, K. (1976), *The site organization: a study of social relationships on construction sites*. Internal Communication, Department of Construction Management, Technical University of Denmark, Copenhagen, Denmark.

Kunda, G. (1992), *Engineering Culture: Control and Commitment in High-Tech Corporation*. Philadelphia: Temple University Press.

Levinthal, D. (1988), "A Survey of Agency Models of Organizations," *Journal of Economic Behavior and Organization*, 9, 153-185.

March, J. G. (1995), *A Primer on Decision Making: How Decisions Happen*. New York: Free Press.

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

Milgrom, P. and J. Roberts (1992), *Economics, Organization and Management*. Prentice-Hall Inc.

Mintzberg, H. (1973), *The Nature of Managerial Work*. New York: Harper & Row, Pub.

Mintzberg, H. (1983), *Power In and Around Organizations*. Englewood Cliffs, NJ: Prentice-Hall Inc.

Morrison, A. (1992), *The New Leaders: Guidelines on Leadership Diversity in America*. San Francisco, CA: Jossey-Bass.

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

Nemeth, C. J. (1985), “Dissent, group process, and creativity: The contribution of minority influence,” in Lawler, E. (Ed.), *Advances in Group Process*. Greenwich, CT: JAI Press.

Nemeth, C. J. (1986), “Differential contributions of majority and minority influence,” *Psychological Review*, 93, 23-32.

Ouchi, W. (1979), “A Conceptual Framework for the Design of Organization Control Mechanisms,” *Management Science*, 25:833-848.

Ouchi, W. (1980), “Markets, bureaucracies, and clans*,” Administrative Science Quarterly*, 34, 21-37.

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

Pelled, L. (1996), “Demographic diversity, conflict, and work group outcomes: An intervening process theory,” *Organization Science*, 7, 615-631.

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

Pondy, L. R. (1967), “Organizational Conflict: Concepts and Models,” *Administrative Science Quarterly*, 12, 296-320.

Schmidt, S. M. and T. A. Kochan (1972), “Conflict: Toward Conceptual Clarity,” *Administrative Science Quarterly*, 17, 359-370.

Shaw, M. E. (1976), *Group Dynamics: The Psychology of Small Group Behavior*. New York: McGraw-Hill.

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). CA, MA: MIT Press.

Simon, H. A. (1997), *Administrative Behavior* (4th ed.). NY: Macmillan (1st ed. 1945).

Smith, K. G., K. A. Smith, J. D. Olian, H. P. Sims, D. P. O'Bannon and J. A. Scully (1994), "Top management team demography and process: The role of social integration and communication," *Administrative Science Quarterly*, 39, 412-438.

Stinchcombe, A. L. (1965), "Social Structure and organizations," in James G. March (Ed.), *Handbook of Organizations*. 142-193. Chicago: Rand McNally.

Tanguiane, A. S. (1990), *Aggregation and Representation of Preferences: Introduction to Mathematical Theory of Democracy*. New York: Springer Verlag.

Thompson, J. D. (1967), *Organizations in Action: Social Science Bases in 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, J. C. Kunz and C. I. Nass (1998), *A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations*. CIFE Working Paper #47, Stanford University.

Van de Ven, A. H. and D. Ferry (1980), *Measuring and Assessing Orgs*. NY: Wiley.

Van de Vliert, E. and C. K. W. De Dreu (1994), "Optimizing performance by conflict stimulation," *International Journal of Conflict Management*, 5, 211-222.

Wagner, W. G., J. Pfeffer and C. A. O'Reilly III (1984), "Organizational Demography and turnover in top management groups," *Admin. Science Quarterly*, 29, 74-92.

Wanous, J. P. and M. A. Youtz (1986), "Solution Diversity and the quality of group decisions," *Academy of Management Journal*, 29: 149-158.

Watson, W., K. Kumar and L. Michaelson (1993), "Cultural diversity's impact on interaction process and performance: Comparing homogeneous and diverse task groups," *Academy of Management Journal*, 36, 590-602.

Weick, K. E. (1979), *The Social Psychology of Organizing*. McGraw-Hill Inc.

Williamson, O. E. (1979), "Transaction-cost economics: The governance of contractual relations," *Journal of Law and Economics*, 22, 3-16.

CHAPTER IV

Designing Quality into Project Organizations through Computational Organizational Simulation[12]

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Abstract

This paper shifts the focus of quality management from measuring and controlling the quality of work processes to the next level upstream—measuring and controlling the quality of the organizations that execute work processes. Starting from an organizational information-processing perspective, we have developed the Virtual Team Alliance (VTA), a complex, coherent computational model of project participants' information-processing behavior that include variables (e.g., activity flexibility and goal incongruency) that are substantively critical to performance of projects. Project participants are endowed with fragments of canonical information-processing micro-behavior (e.g., attention allocation, information processing, communication, and decision-making), and then assembled into networks of actors and tasks to represent project organizations. Through simulation of project participants' micro-level behavior, our computational model generates useful and measurable emergent quantitative performance predictions regarding the efficiency and quality of a project's configuration of work processes and organizational structure. The model produces two measures of efficiency—project duration and cost—and three measures of work process quality—problem-solving quality, coordination quality, and decision-making quality. In addition to providing a project manager with measures to support specific and detailed organizational design decisions involving trade-offs between cost, duration, and work process quality, our model predicts organizational risks that might adversely affect project performance. Users can identify and test feasible, detailed, and useful interventions to mitigate organizational risks contingently. We prospectively applied our model early in the development process of an industrial project team within the aerospace industry. Our model forecasted backlogs arising from extra coordination and rework and the resulting problems that might occur without organizational change. Based on simulations and analysis of our model, we made specific recommendations to the project manager for improving work process performance. After considering our recommendations, the cooperating manager intervened in the engineering process to reduce some of the organizational risks that we predicted might adversely affect project performance. In our subsequent observations of the project, the potential organizational risks that our model had initially identified as being likely to affect project performance adversely were avoided by the manager's intervention.

Key Words and Phrases: Computational Organizational Design and Analysis, Contingency Theory, External Validation, Intervention Study, Total Quality Management.

1. Introduction

The increasingly competitive global marketplace in which organizations must compete has necessitated a progressively stronger emphasis on quality management within organizations (*Business Week*, 1992). Organizations reengineer their organizations and

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work process to improve the quality and efficiency of their products and services. Organizational reengineering typically involves radically redesigning work processes as fast-paced "projects." Organizations eliminate unnecessary process steps, streamline work flow for value-adding steps, simplify organizational structure, and increase accountability through the identification of persons with single point responsibility for each work process (Davenport, 1993; Davidow and Malone, 1992; Hammer and Champy, 1993). Changes in work processes have to overcome significant cultural and social inertia, and required financial investments in these transformations are non-trivial. Thus, before they are undertaken, their potential benefits need to be well understood.

Given the need to minimize time to market for increasingly complex products, fast-paced product development efforts are not easy. The project team needs work process flexibility to come up with solutions to tightened and challenging performance targets (Brown and Eisenhardt, 1997). Complex exceptions, extending beyond the information shortfalls characterized by Galbraith (1977), are endemic to this kind of semi-routine work.

Executing projects concurrently increases the impact of exceptions and, therefore, greatly increases the volume of coordination and rework. Organizations must address the high coordination and rework demand brought on by shortened and “concurrent” schedules, in which activities that were previously performed sequentially are instead performed concurrently. Effective and efficient organizational designs can mitigate the increase in coordination and rework as projects become increasingly non-routine and fast-paced. Yet traditional organizational contingency theory can predict neither the magnitude nor the specific locus of the increased coordination and rework demand. Lacking the kinds of detailed and reliable analysis tools that are universally used to model and simulate the behavior of proposed artifacts and processes in many engineering domains, "organizational reengineers" must currently design their organizations by subjective trial-and-error adaptation.

To provide organizational design and analysis tools, a growing number of researchers with expertise in mathematical modeling, formal logic, organizational and communication theory, sophisticated statistical techniques, visualization, user-interface, and computer programming has coalesced into a discipline called Computational and

Mathematical Organizational Theory (CMOT) (e.g., Carley and Prietula, 1994). Using modern desktop computers and techniques in artificial intelligence, this effort represents a new area of scholarship that attempts to model, explicitly and dynamically, the attributes, interrelationships, and behavior of a network of agents, based on theoretical generative micro-mechanisms offered by one or more social scientific theories (Carley, 1995). We believe that the most promising approach for "engineering" organizations will come from the field of CMOT. Accordingly, we have chosen to use a computational model of organizations in order to conduct alternative experiments investigating the relationship between organizational structure, participants' profiles, and project efficiency and work process quality.

Grounded in CMOT, this paper presents a new approach to quality management. We shift the focus of quality management from *measuring and controlling the quality of work processes* to the next level upstream – *measuring and controlling the quality of the organizations that execute work processes*. We model the behavior of the organizations at a micro-level (i.e., the level of individual actions and interactions) and use simulation to predict emergent project efficiency and work process quality. We attempt to refute the null-hypothesis that different organizational designs do not affect work process quality. While testing the null-hypothesis, we identify organizational behavior that influences work process quality, specify the indicators by which work process quality is measured, and formalize and model the mechanisms by which those variables affect work process quality.

Because of the intricacy of the problem of designing quality into real-world organizations, we used a case-study approach to illustrate the application of our model (Eisenhardt, 1989). Following a review of the quality management point of departure and presentation of research objectives, this paper summarizes the results of the application of our model to two portions of an ongoing launch vehicle project. We then describe in detail a spacecraft propulsion subsystem project that we will later use to illustrate and validate our computational organizational model. Section 5 reviews our computational organizational modeling point of departure. Section 6 describes our extended information-processing conceptualization of a project organization. Section 7 discusses how we link an actor’s information-processing behavior to project performance and quality measures. Thereafter, we present computational organizational experiments using our case study model. We conclude our paper with a summary of our practical and theoretical contributions, limitations of our model, and our suggestions for future work.

2. A Quality Management Point of Departure

Prior to the 1960's, assessments of quality were primarily based on measures of the quality of the end product (e.g., dimensional tolerances, or number of functional defects). Quality efforts focused on inspecting parts and rejecting "defects." As a result, quality assessments were conducted at the very end of the work process rather than during or even before project execution. Many firms did not even attempt to evaluate quality through internal mechanisms, but relied on customer response and feedback. This passive approach to quality control was costly and inefficient, since the activities and work processes that gave rise to products were already well established and not easily modified by the time quality defects were identified.

Since the 1960's, however, there has been a progressive trend towards greater awareness of quality issues and toward moving the focus of quality control efforts further upstream in the work process. There was a shift from measuring the outputs of production to monitoring and controlling work processes. As researchers and managers developed better insights into statistical quality control, the effort to improve quality moved even further upstream towards the planning and execution of work processes. To address the increased interest in quality, numerous quality programs, standards, and awards were eventually instituted. Some approaches to increasing quality in organizations were promoted by researchers such as W. Edwards Deming (1986), Joseph Juran (1974), and Kaoru Ishikawa (1985), while others imitated the approach used by successful firms such as Xerox or Ford. Still others were developed by classification societies, including Det Norske Veritas, the American Bureau of Shipping, as well as the International Standards Organizations. The United States government has encouraged this widespread emphasis on quality through introduction of the Malcolm Baldrige Quality Award *(U.S. Department of Commerce*, 1996). Like its American equivalent, the European Community's European Quality Award (*European Foundation for Quality Management*, 1996) is awarded on the basis of superior work process quality.

Despite the prevalence of Total Quality Management (TQM) methods in industry, there is, in fact, no coherent theoretical framework underlying it (Anderson *et al.*, 1994). Some researchers argue that TQM methods simply repackage many older management techniques (Lawler *et al.*, 1992; Pfeffer, 1994; Schonberger, 1992). For example, one group of researchers sees TQM as operationalizing ideas from the school of scientific management (Anderson *et al.*, 1994; Dean and Bowen, 1994). Others feel that TQM represents a shift in organizational culture rather than a means of providing explicit methods for improving quality (Lawler, 1994; Waldman, 1994). The literature on TQM methods makes it clear that a wide range of disparate attitudes and beliefs exist concerning the nature of TQM. However, there is a consensus among researchers concerning TQMs most important general themes. Among these are a focus on the customer, continuous improvement, and organization-wide collaboration through teamwork and employee involvement (Garvin, 1988; Dean and Bowen, 1994; Waldman, 1994; Spencer, 1994; Hackman and Wageman, 1995).

Advocates of the TQM approach assume that holistic TQM methods are universally beneficial for all organizations (Crosby, 1979; Deming, 1982; Juran, 1992). Rejecting this assumption, Sitkin *et al.*, (1994) have attempted to extend TQM to take into consideration the specific characteristics of an organization and its environment before prescribing methods to improve quality. In Sitkin's opinion, TQM methods must be adapted to fit the level of uncertainty, non-routineness, and stability within the organization.

Organizations now possess universal TQM methods and criteria with which to evaluate work process quality. The TQM slogan summarizes ideas with real value, but it provides too little guidance about what the improved organization might look like. Managers still lack methods to anticipate how detailed changes to the organization or to the work process will affect organizational performance and quality. Beyond relying on their own experience and intuitions, decision-makers cannot systematically predict how alternative organizational structures, communication tools, personnel profiles, or work processes will promote or degrade particular dimensions of quality. The challenge facing organizational decision makers and organizational researchers today is to design quality into organizations instead of developing further ways to improve quality after deficiencies have already arisen in work processes or their outputs. Their task is complicated by the fact that increases in quality may require a trade-off in other performance measures, such as project capital costs and durations. Related challenges that practitioners must include are to anticipate risks in the organization, to identify interventions to mitigate risks, and to develop measurable objectives that allow monitoring of the effectiveness of interventions.

3. Research Objectives

Having presented the quality management point of departure, our research has two objectives: predicting quality performance for a given organization and designing high quality organizations contingently.

- **Predict Quality Performance:** Understanding the relationship between the structure of the organization and the quality of its work process is prohibitively difficult because of the number of factors that must be considered simultaneously to predict emergent organizational behavior. A single change within the organization can have second and third order effects and may interact with other variables in ways managers cannot intuit to affect the quality of the work process. Hence, a manager is unlikely to be able to make specific, quantitative predictions regarding the likely impact of any change in organizational parameters on the quality of the work process. Through our research, we hope to create tools and methods that will allow organizational designers to predict how changes to organization structure or work processes will affect quality.
- **Enable Detailed and Contingent Design of High Quality Organizations:** Holistic Total Quality Management techniques assume that certain practices will universally increase quality in all organizations (Crosby, 1979; Deming, 1982; Juran, 1992). Much organizational research indicates, however, that there does not exist a single best way to organize and that different organizational methods aimed at improving performance are not equally effective for different organizations (Galbraith, 1973; Thompson, 1967). While not all ways of organizing and structuring are equally good, there may be more than one good way for an organization to structure or organize (Gresov and Drazin, 1997). We hope to address the limitations of *holistic* and *universal* prescriptions of the TQM framework and increase its utility and

applicability by incorporating newer insights from CMOT to develop a more powerful *detailed* and *contingent* approach to designing quality into organizations.

It is a non-trivial problem to create a computational organizational model that provides answers to both of these research questions and at the same time is useful. A computational organizational model is only useful if

1. it enables the project manager to identify risks that might affect project performance adversely,
2. it identifies feasible and useful interventions to mitigate risks, and
3. it predicts the effect of potential interventions on project efficiency and work process quality.

Consequently, the only way to judge the usefulness of a computational organizational model is through an intervention study (Thomsen *et al.*, 1998c). In the following section, we describe test cases from the aerospace industry, on one of which we conducted an intervention study.

4. Case Studies from the Aerospace Industry

It is not feasible to report the contexts and results of several multi-year, multi-person cases within a single journal article. In this section, we summarize the results from a space launch vehicle development test case and refer the interested reader to Thomsen *et al.*, (1998c) for more information. We then provide an in-depth description of a Spacecraft Propulsion Subsystem Development intervention study we conducted using our Virtual Team Alliance (VTA) computational organizational model.

4.1 Launch Vehicle Development

The first project we modeled was the development of a new launch vehicle, a commercial version of military missile that had to be implemented substantially faster in a fiercely competitive global market. Much of the work was outsourced to external component suppliers whose goals were more or less congruent with those of the prime contractor. We introduced mechanisms of goal incongruency into the VTA model, collected data from the launch vehicle project regarding participant goals contemporaneous with project execution, and compared observations with simulated predictions. We learned that the goal incongruency model usefully predicts important effects on project performance and quality of changing levels of goal incongruency between project participants.

The simulation model described the organizations, the plans, and it predicted the risks. For this project, VTA clearly predicted the risk of backlog in the external team developing an outsourced component of the avionics package. As a result of this backlog, VTA predicted a serious quality problem and resulting risk of delays. Because of lack of sufficient prior experience with the modeling methodology, neither the investigators nor the project management intervened based on this prediction. The backlog and its impacts later materialized exactly when and where predicted and had to be managed with a subsequent high impact on project cost and schedule (Thomsen *et al.*, 1998c).

With newly gained confidence, we prospectively applied the simulation model early in the design of a subsequent aerospace project: development, procurement and testing of a critical component of a Spacecraft Propulsion Subsystem. The following sub-section describes this test case.

4.2 Spacecraft Propulsion Subsystem Development

4.2.1 Case Description

Our second case study is taken from the aerospace industry and revolves around the development of a new spacecraft propulsion subsystem for positioning communication satellites into orbit. The commercial aerospace industry has faced a number of challenges in the past few years. Because of a highly competitive communications marketplace, the next generation of communication satellites must offer customers lower cost, reduced weight, and reduced lead-time prior to launch. To meet these challenges, and to be capable of accommodating many different payloads, our cooperating aerospace company decided to develop a new type of satellite. The satellite is launched into low orbit by a booster rocket. Once located in low orbit, the satellite itself has a small rocket motor for maneuvering more precisely into the final, pre-specified orbit.

We studied the development of a new generation of pyrovalves (i.e., a valve actuated by an explosive charge that shuts off the rocket motor fuel line) for the new satellites.

Challenges that the developers of this new generation of pyrovalves face are to minimize the subsystem mass, gas leakage, and power consumption. To meet these challenges, the pyrovalve developers depend on making complex technical trade-offs applying advanced engineering knowledge. For example, in some cases, the adoption of an advanced material (e.g., titanium) or design in one area may result in an undesirable effect in another area. Lightweight structural material provides less radiation shielding than, say, aluminum, thereby requiring the possible addition of more shielding material around sensitive electronic components, which, in turn, offsets some of the mass advantages of the lightweight material. The development of a next generation pyrovalve can therefore be characterized as a non-routine process conducted by a team of engineering professionals.

The model we developed in our VTA framework represents the pyrovalve project team in the new Spacecraft Propulsion System Development Program. The pyrovalve project is headquartered in California, where the bulk of project activities involve internal coordination between the different groups directly working on the project, as well as system integration and test. Our cooperating partner has facilities in Colorado to handle specification details, engineering revisions, and external coordination with outside organizations such as NASA. A contractor in Florida is performing the design and assembly of the pyrovalve. All procurement responsibility is given to another contractor located in Washington. We modeled the development phase of the project, which began on November 1, 1996 and was scheduled, for completion on August 1, 1997.

We prospectively obtained data on the organizations through semi-structured interviews with key project members and project specifications (Statement of Work). We then used this data to construct the models, in conjunction with continuous input from project participants. Fifteen interviews were conducted in the early autumn of 1996 with project participants at all levels of the hierarchy. To evaluate our results, we typically consulted project team leaders on a bi-weekly basis. At each stage of development of the model, project participants confirmed input data. Figure 1 shows our model of the pyrovalve development project work process and organizational hierarchy.

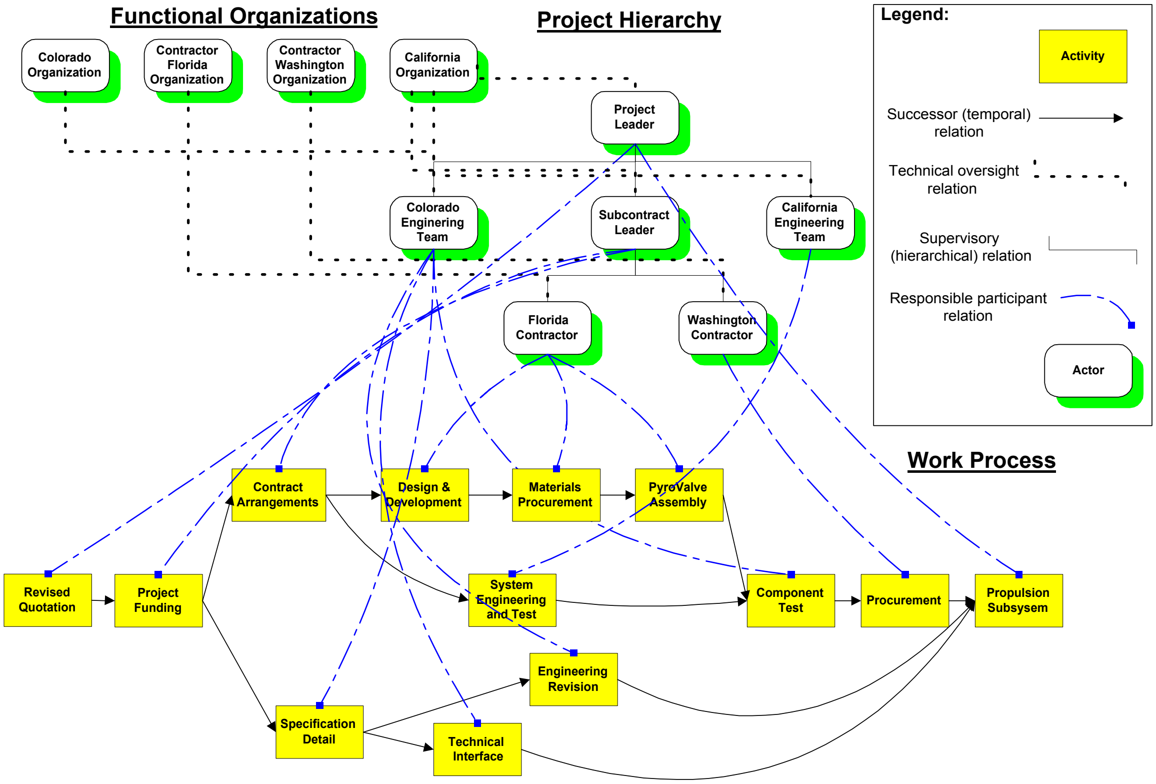

***Figure 1*: The Pyrovalve Development Project Work Process and Organizational Hierarchy**. In our conceptual model, a project includes participants (embedded in a hierarchical organizational structure) and the activities (the Critical Path (CPM) model), which are interrelated. That is, each project participant fills a position in the project organizational hierarchy and works on one or more activities. The organizational structure and the interdependence between activities generate requirements for coordination and communication between the particular participants responsible for those activities. The Pyrovalve project has a matrix structure in which subordinates report to two supervisors at the same time—one supervisor responsible for the project, and one responsible for a particular functional discipline in subordinates' "home" organization. To incorporate this influence of functional managers in our model, we represent functional managers explicitly. In section 6, we provide a detailed description of the conceptual model.

4.2.2 Managerial Organizational Challenges

Three main organizational challenges faced by the project manager of the Pyrovalve project are described below:

- **A Shared Understanding of Goal Trade-offs:** The earlier, military-related focus on product performance at virtually any price has been replaced by a focus on product cost-effectiveness, timeliness, and quality as our cooperating partner's most important organizational goals. These three drivers (cost, schedule, and quality) are not independent variables. Given the cost-schedule-quality priority for the new spacecraft, the design approach is very sensitive to cost and must allow capability to within cost and schedule to define the quality. Quality requirements and cost-driven capabilities must find a middle ground where adequate quality can be achieved for a reasonable cost. However, most of the pyrovalve project participants have gone through extensive education and training in classified military product development projects, becoming steeped in the "product performance at any price culture" of such programs. The specific question that the project manager had to consider was the following: *Should I instantiate, and continuously encourage, project participants to formalize their priorities in the form of goal trade-off tables*[13]*? Such trade-off tables create a set of guideposts that allow interdependent actors to make technical decisions more quickly and consistently. They can thus increase the likelihood that required quality standards, along with tightened cost and duration goals are meet.*

- **Goal Alignment:** The pyrovalve project was assembled from multiple participating organizations, and consisted of multiple constituent sub-teams. The participants inevitably include members whose goals differ not only within the team but also across teams. The multi-disciplinary and multi-cultural nature of the project increases the degree of goal incongruency within the project team. This could eventually lead to misunderstandings or conflicts between project participants if the project is not well managed. The situation is exacerbated by the dynamic composition of the project team because project personnel generally have fewer opportunities to gain familiarity with each other in this setting than in more stable, permanent organizational structures. The specific question that the project manager had to consider was the following: *How can I ensure that project participants with potentially incongruent goals work efficiently and cooperatively, integrating their local solutions with those of other actors to build an overall solution that meets the goals of the project?*
- **Micro-involvement:** The pyrovalve project is difficult to plan and manage, with demanding customers, tight budgets and schedules, complex technology, and project

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[13] A goal trade-off table is a shared understanding of the relative goal priority and goal trade-offs, e.g., a detailed estimate of the value of saving a day of schedule, or of incorporating a feature in the product.

> work progressing concurrently in geographically dispersed locations. A senior executive at our cooperating partner characterized the main organizational challenge as lessening the supervisor's preference for micro-management, a habit that evolved from previous military product development efforts. Project teams need to work unencumbered by close managerial scrutiny, highly formal detailed plans, supervisory approvals and other "bureaucratic delays." On the other hand, even though work autonomy is needed, quality problems, cost overruns and missed deadlines might be the result of too little managerial involvement. The specific question that the project manager had to consider was the following: *How much involvement in the day-to-day affairs and activities of subordinates should I assume to meet overall cost, duration, and quality standards on the project?*

Neither Critical Path (CPM) models nor TQM can give useful answers to these questions. CPM models assume an idealized situation in which concurrent activities for different parts of the project deliverable are independent and uncoupled. CPM models also view project participants as "omnipotent clairvoyants" who always act—they do not interact!—in perfect harmony with the project plan, and CPM models assume there is only one way to perform the tasks on the project (Moder *et al.*, 1983). TQM gives holistic, universal suggestions, but not detailed practical, contingent recommendations. As Sitkin (1994) explains, the TQM approach does not consider the particular structure and environment of each organization. Thus, the project manager has to rely on his own intuitions and experience to design an appropriate organization and project workflow to meet his challenges.

4.2.3 Modeling Challenges

We developed a model that had the potential to provide the project manager with insights into his managerial organizational challenges. We focused on keeping our representation rich but, at the same time, parsimonious enough to maintain theoretical transparency and modeling feasibility. Two concepts seemed to us to be of particular importance in a computational organizational model of the pyrovalve project—*goal incongruency* and the managers' *preference for micro-management.*

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 the professionals who carry it out. Professional actors from different occupational specialities have novel perspectives about the best solutions (Mock and Morse, 1977). They assign different weights and rankings to the various criteria or goals by which they evaluate each solution (judgment). Typically, these criteria include such factors as cost, duration, and quality. Based on their rankings, actors will exhibit a preference for one solution over others (interpretation). We refer to the difference in ranking of criteria as "goal incongruency" between actors. Representing goals will allow reasoning about actor and task performance, given differences in actor beliefs or preferences.

Building on Mintzberg's (1973) categorization, as well as other theories of leadership, Burton and Obel (1995) demonstrated that leadership styles can be categorized into one of two categories based on how managers process information and make decisions. The difference between the two categories is rooted in whether or not a manager has a preference for micro-management (i.e., the habit of becoming heavily involved in the day-to-day affairs and activities of subordinates). The effect of goal incongruency on vertical relationships will either be magnified or mitigated, depending on the leadership style of the manager involved. "Micro-managers" will react more strongly to goal incongruency than non-micro-managers. Such managers, for example, will engage in greater monitoring and are likely to take decision-making power away from a subordinate whom they perceive to have goals that are incongruent with their own.

The following section reviews our computational organizational modeling point of departure. Section 6 describes the information-processing conceptualization of project organizations and section 7 describes how we link an actor's information-processing behavior to project performance measures. We subsequently present and discuss computational experiments that provide the project manager with insights into his organizational challenges.

5. Computational Models of Organizations

Three basic types of computational models are in use today for analyzing the behavior of complex organizational systems—formal mathematical models, heuristic diagnosis models, and simulation models (Levitt, 1996). Mathematical models are well suited to theorem proving in the study of single, isolated organizational problems. Their chief advantage lies in their internal consistency when applied to problems of this type, while their greatest weaknesses are oversimplification and the difficulty of external validation. Heuristic diagnosis models are based on the formalization of diagnosis rules and their implementation in a computer model. They are relatively simple to develop once effective diagnostic heuristics have been well defined. However, they tend to be relatively brittle compared to simulation models. That is, their performance and effectiveness drop off dramatically outside the narrow domain in which the heuristics they incorporate are applicable (Buchanan and Shortliffe, 1984). In model-based simulation models, quantitative relations among variables are replaced with objects interacting in chains of events. We argue that model-based simulations better represent the dynamic behavior of actual complex organizations because relevant objects in the real world are specifically represented by corresponding elements in the model. The advent of object-oriented simulation frameworks, such as IntelliCorp's Kappa (*IntelliCorp*, 1994), have allowed simulation models to be developed rapidly and to support more complex what-if experimentation than would be possible with mathematical models.

In light of the many variables that must be considered in studying emergent project behavior arising from the interaction of many actors, we have chosen to implement our framework through a simulation model of organizational behavior. Specifically, we decided to ground our models in the Virtual Team Alliance (VTA) simulation framework (Cohen, 1992; Christiansen, 1993; Jin and Levitt, 1996; Thomsen *et al.*, 1998b). The decision to use VTA over other modeling frameworks, such as the garbage can model and its derivatives (Cohen *et al.*, 1972; Masuch and Lapotin, 1989), was made for several reasons. First, it afforded organizational engineering based on actor and task modeling at a level of detail far greater than that of any other simulation platform. Second, VTA makes possible the creation of measures of organizational performance by simulating the actions of and interactions between individual actors as they perform their assigned activities, which are highly specific and quantitative. Finally, VTA is theoretically grounded in the information-processing contingency view of organizations, which is the preeminent theoretical approach to understanding and predicting organizational performance (Pfeffer, 1996, p. 70).

The next section describes how actors are constrained by project activities and how project requirements choreograph interaction in a project organization.

6. The VTA Model of Project Organizations

The purpose of this paper is not to present the "nitty-gritty" details of the VTA model, but, rather, to provide an example how we link Total Quality Management (TQM) theory with theory and practice of computational organizational modeling and simulation. This section provides the reader with an overview of VTA model. Further information about the workings and validation of the VTA model can be found in (Thomsen *et al*., 1998a; 1998b; 1998c).

Our objective is to analyze and predict project behavior by simulating actions of and interactions between individual actors. We assume that the project manager can iteratively decompose overall project objectives into the lower-level, concrete requirements. Research has shown that detailed requirements actually drive the behavior of individual participants, not higher-level abstract objectives (e.g., Locke and Latham, 1990). In addition, to be tractable for analysis in our model, the project manager must be able to relate requirements to work processes (given by the CPM), to fill organizational roles or positions with project participants, and to pre-assign activities to different, specialized individuals or subgroups with undifferentiated members, termed “actors.” (Figure 1). It was surprisingly easy and fast (about three meetings that lasted for about one hour) for our cooperating project manager to describe the activities, actors and their attributes (indicating the relevance of our conceptualization to practical project management).

Because we are concerned with problem solving in relation to the activities in the CPM (and the need to exchange information in response to that problem solving), we abstract away the technical engineering content of the requirements to which the specialist contributes. We assume that the technical engineering content of the requirements does not vary in relation to changes in organizational design. In contrast, decision analysis or economic models, such as multi-criteria decision making and collective choice, presume that all alternatives for all requirements can be ordered with respect to utility functions, adopting greater values at better alternatives (Tanguiane, 1990). Modeling and ordering all alternatives was neither feasible nor necessary on the case project.

Within our model, each CPM activity is characterized by values that represent the levels of complexity, uncertainty, flexibility, and interdependence (with outside activities) associated with that activity. These activity attributes determine what type of information-processing behavior the responsible actors engage in. We derive the complexity of an activity based on the number of requirements that must be considered in finding a solution to the activity and on the difficulty in achieving each of the requirements. Similarly, we define the activity interdependence strength as the sum of the requirement complexity of the requirements connecting activities (Thomsen *et al.*, 1998a). Requirement complexity is a measure of the number of potential solutions to a requirement and is measured by "activity flexibility."

Activity flexibility represents the number of alternative means that exist for executing the activity. That workers even have the opportunity to select solutions differentially is grounded in the fact that work packages are generally assigned with a considerable degree of looseness or non-specificity by managers. Especially in organizations with TQM policies that seek to empower the individual worker, it is common practice to specify only general requirements and to give designers considerable flexibility in choosing working approaches or methods. The amount of flexibility that can be permitted without jeopardizing product quality depends on the nature of any particular work package, the skill and experience of participants in the organization, and the industry in which the organization is embedded.

The advantage of not overspecifying work lies in the fact that workers are then able to apply their own creativity and expertise in deriving optimal solutions and to work unencumbered by unnecessary restrictions or specifications. The main disadvantage of not overspecifying work is that it could give rise to a vast number of exceptions. These give rise to significant volumes of communication aimed at reconciling interdependent activities. Traditionally, the work process flexibility on our cooperating partner's projects has been low. Our cooperating partner is moving to provide more flexibility in the work process so that projects have the necessary versatility to meet tightened performance standards. We asked the project manager to estimate activity flexibility using a Likert scale from 1 to 9. His estimates ranged from 9 on the Contract Arrangements, 5 on the Design and Development, to 2 on Engineering Revision.

> Activity flexibility, complexity, and interdependence strength are derived based on the level of definition of project requirements at the beginning of a project. In our case study project, the environment, e.g., the parent organization, continuously refines some requirements during the course of the project. Activity uncertainty results in more communication between interdependent activities. We asked the project manager to estimate activity uncertainty using a Likert scale from 1 to 9. His estimates varied from 9 on the System Engineering activity to 2 on the Pyrovalve Assembly activity.

Professionals, including the actors who composed the pyrovalve team, tend to have differing goals and values that generally lead them to have competing preferences among alternatives (Werkman, 1990). 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. The performance of an organization depends on which solutions are implemented to fulfill each of its goals and the ability and goal priority of individual actors itself influence the selection of these solutions. Thus, an actor's actions are intimately related to organizational performance. Therefore, the most important part of our computational model is the actor model, which describes the characteristics of the knowledgeable people involved in the project.

Their skills, length of task experience, and goal priorities define actors. We make a number of assumptions concerning the nature and characteristics of VTA actors. First, actors are sincerely motivated when searching for the best possible solution. In preferring one solution to another, actors are genuinely interested in implementing the solution that they believe best serves the interests of the organization, i.e., actors are altruistic, but not necessary goal congruent. We developed a methodology for gathering data on goal incongruency within the pyrovalve project team based on Chatman's (1991) card-sort method. We asked the project manager to list the most important project goals (e.g., completing the project on schedule, staying under budget). 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. . Indeed, when we collected data on the project, higher-level actors focused on cost, 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 (cf. Chiles and McMackin, 1996; Ghoshal and Moran, 1996; Nass, 1986).

Second, actors are boundedly rational, which means that actors do not have all of the information and cognitive resources they need to become ideal problem solvers. The limited cognitive information-processing capabilities of actors results in their becoming overloaded when they must attend to an abundance of primary work, communication demands, and exception-handling duties. Third, the priorities that give rise to goal incongruencies can change between projects, but they remain constant over the course of a single project. In other words, goal incongruencies do not fluctuate during project execution. Fourth, actors have a limited ability to learn from experience over the duration of the project. As exceptions are detected and corrected, the actor will tend to generate fewer exceptions downstream in the work process.

In accordance with the literature on management science, our model posits two functions for the organizational hierarchy. In one capacity, it is a proactive tool used by managers to control the behavior of subordinates (Ouchi, 1979; Eisenhardt, 1985). Managerial prescriptions are issued down the hierarchy, and reports from subordinates flow upwards. In another capacity, it is a reactive exception handling device designed to respond to exceptions (Galbraith, 1977). Once an exception has been generated in our model, a probabilistic function determines where in the hierarchy it will be handled. This is expressed as a matrix in which columns indicate the level of centralization of decision-making responsibility within the organization (high, medium, low) and rows indicate organizational position (project manager, sub-team leader, sub-team). Decision-making behavior is a function of organizational position. A shift in organizational position exposes the employee to new "facts" and phenomena, to a new network of communications, and to new goals. Based on Simon’s (1997a) theory that the cognitive limitations of human actors will cause them to be more likely to identify with the goals for which they are most directly responsible, higher-level actors are assumed to be motivated by project-level goals rather than requirements for activities. By virtue of their global perspective on the project, managers are assumed to have a greater awareness of the severe ramifications that a failure in one activity could have for other interdependent activities. Hence, higher-level actors in our model tend to favor rework when exceptions are detected. Once the exception has been detected, reviewed, and attended to by the supervisor, a "ignore," "quick-fix," or "rework" decision is made about the exception.

Based on these attributes of activities, actors, and organizations, we understand an actor’s actions in our model to consist of three different types of work. The first type, referred to as primary work, reflects the effort that is spent solely on tasks that contribute tangibly to the completion of an activity. Primary work generates information that needs to be processed by actors. The actors must also engage in a certain amount of secondary communication work in order to coordinate with other actors and to resolve questions and discrepancies concerning primary work. This second type of work, called coordination work, reflects the work that is devoted to coordinating and communicating with other actors through communication tools. The third type, exception-handling work, represents the effort dedicated to resolving exceptions that arise during activity execution. All three types of work can be viewed in terms of the amount of information processing that is required to execute them. Hence, we use “work volumes” to indicate the information-processing load required to perform a task or communication.

In conclusion, we conceptualize projects as a series of “actor” objects interacting in a network of communication channels. Attributes of and relationships between the work process objects define the amount of interaction. A VTA dynamic simulation of the information-processing behavior of our model directly provides measures of project duration (i.e., the elapsed time along the longest or “critical” path through the CPM network of activities), and the project cost (i.e., the total work-hours spent to perform all activities involved in the project). However, developing useful measures of project work process quality is much more challenging.

The next section explains how we define work process quality measures that pertain to primary work, coordination work, and exception-handling work.

7. Linking Actor Behavior to Work Process Quality Measures

Given that the work process consists of three types of work, we represent quality for each of these types, rather than simply measuring the aggregate quality of the overall work process. To this end, we developed three different indices of quality: problem-solving quality, coordination quality, and decision-making quality. The detailed level of granularity at which VTA simulates organizational behavior allows us to measure work process quality for each type of work. We present an information-processing operationalization of each of these indexes below.

7.1 Primary Work—Problem-solving Quality

For this research, we consider exceptions to be deviations from managerial prescriptions. We make a distinction between two different kinds of exceptions, technical errors and non-conformances, each of which have different effects on the organization and the actors.

- **Technical Errors:** Errors of judgment (technical oversight) and errors of skill (technical incompetence or lack of diligence) are both considered technical errors. Technical errors are always nonproductive, and could have been avoided had the responsible actor been more circumspect or technically proficient.
- **Non-conformances:** Unlike technical errors, non-conformances are not inherently and categorically undesirable. In this case, the actor responsible for completing the activity has not made mistakes. It has deliberately chosen to use different methods to achieve the goals of the activity than that anticipated by the manager of the project plan (i.e., the final product will not necessarily be defective if the non-conformance is not remediated).

The probability that an actor will generate a non-conformance depends on the level of goal incongruency between the actor and supervisor and the potential size of the solution space of the associated activity (measured by activity flexibility), as well as several dynamic behavioral processes. The probability that a non-conformance is productive or counterproductive depends primarily on the relative skill of the manager and the subordinate and secondarily on the history of behavioral interactions between project participants during the project execution (Thomsen *et al*., 1998b). For example, we might imagine that the contractor from Florida uses a light material in creating a design part that satisfies all the design and development goals concurrently despite the subcontract leader's assertions that a design based on that material could not be developed. Although the Contractor's work does not adhere to the Subcontract Leader's original prescriptions, the non-conformance is productive.

We define *Problem-solving Quality* as *the ratio between [(productive non-conformances) minus (technical errors and counterproductive non-conformances)] to (total number of exceptions)*. As more good ideas are generated, quality increases, and as more bad ideas are generated, quality decreases.

7.2 Coordination Work—Coordination Quality

Project actors try to work cooperatively. They use their local expertise, resources, and information to formulate partial solutions and they integrate their solutions with those of other actors to build an overall solution that meets the goals of the pyrovalve system. Such work involves actors with different perspectives applying their knowledge bases and integrating their solutions through communication. For an engineering design task in which coordination is crucial, observation suggests that actors easily tend to become backlogged with communications. The higher the backlog, i.e., the number of items in the actor's in-basket, the higher is the risk that the actor will not attend to the communication in time to address the coordination need that spawned it.

Specifically, we define *Coordination Quality* as *the simulated number of attended communications divided by the total number of communications*. Non-attended communications are communications that are not processed because of negligence or overload on the part of the actor responsible for processing the communication. Non-attended communications lead to breakdowns in coordination, since important requests for information may not be heeded or vital information may not be received. Therefore, the more communications are attended to, the lower the probability that misunderstandings or lack of information will degrade the performance of the project.

7.3 Exception-handling Work—Decision-making Quality

Actors in different organizational positions might make different types of decisions regarding the same exception. Therefore, the distribution of power to make decisions in the organization will determine what types of decisions are made about the project in response to exceptions (technical errors and non-conformances). Despite the high priority of an exception, a supervisor may not have a chance to attend to the exception within a reasonable length of time. As a result, the reporting actor has to make a decision about how to handle the exception in a "delegation-by-default" mode. Hence, the actor who is supposed to make the decision does not, and the Decision-making Quality will degrade since the decision made by the subordinate may be different from the one prescribed by the management decision-making policy. Overloaded managers will cause more delegation-by-default decisions to be made by their subordinates. In addition, each exception that has not been detected represents a failure of the organization's ability to monitor its own behavior. A low proportion of detected exceptions to total exceptions indicates that the existing exception detection system is flawed.

Specifically, we define *Decision-making Quality* as *the ratio of (the number of exceptions decided upon by the appropriate personnel in a timely manner) to (total number of exceptions)*.

The problem-solving, coordination, and decision-making quality measures, combined with additional measures for project cost and duration, provide metrics for evaluating the efficacy of different organizational designs at multiple levels of analysis: particular actor, sub-teams, or the entire project.

8. Computational Experiments and Results

The scientific purpose of our experimentation program was to find evidence that refutes our null-hypothesis that different organizational designs do not affect work process quality (section 1) and provide answers to our research questions (section 3). Application purposes are to illustrate how our model can be used to design quality into organizations and to furnish project managers with guidance on the kinds of managerial challenges set out in section 4.

Our simulation results from the case model can be divided into two categories. The first set of results involves the straightforward predictions made by our model regarding the future behavior and performance of the actual project. The second set of results pertains to the data we obtained from a series of what-if experiments, in which our model predicted the likely performance of the project team.

8.1 Model Predictions for the Project Team: Initial Conditions

The dynamic VTA simulation of the information-processing behavior of our model for the project predicted the risk of severe bottlenecks within two of its subteams, the Colorado Engineering Team (Figure 2) and the Florida Contractor team. Of the two, the overload on the Colorado Engineering team was greater. Serious coordination backlogs could significantly increase time and cost for the project. Indeed, our model predicted a 30% increase in project duration (Figure 2) and a 10% increase in project cost compared to the CPM model.

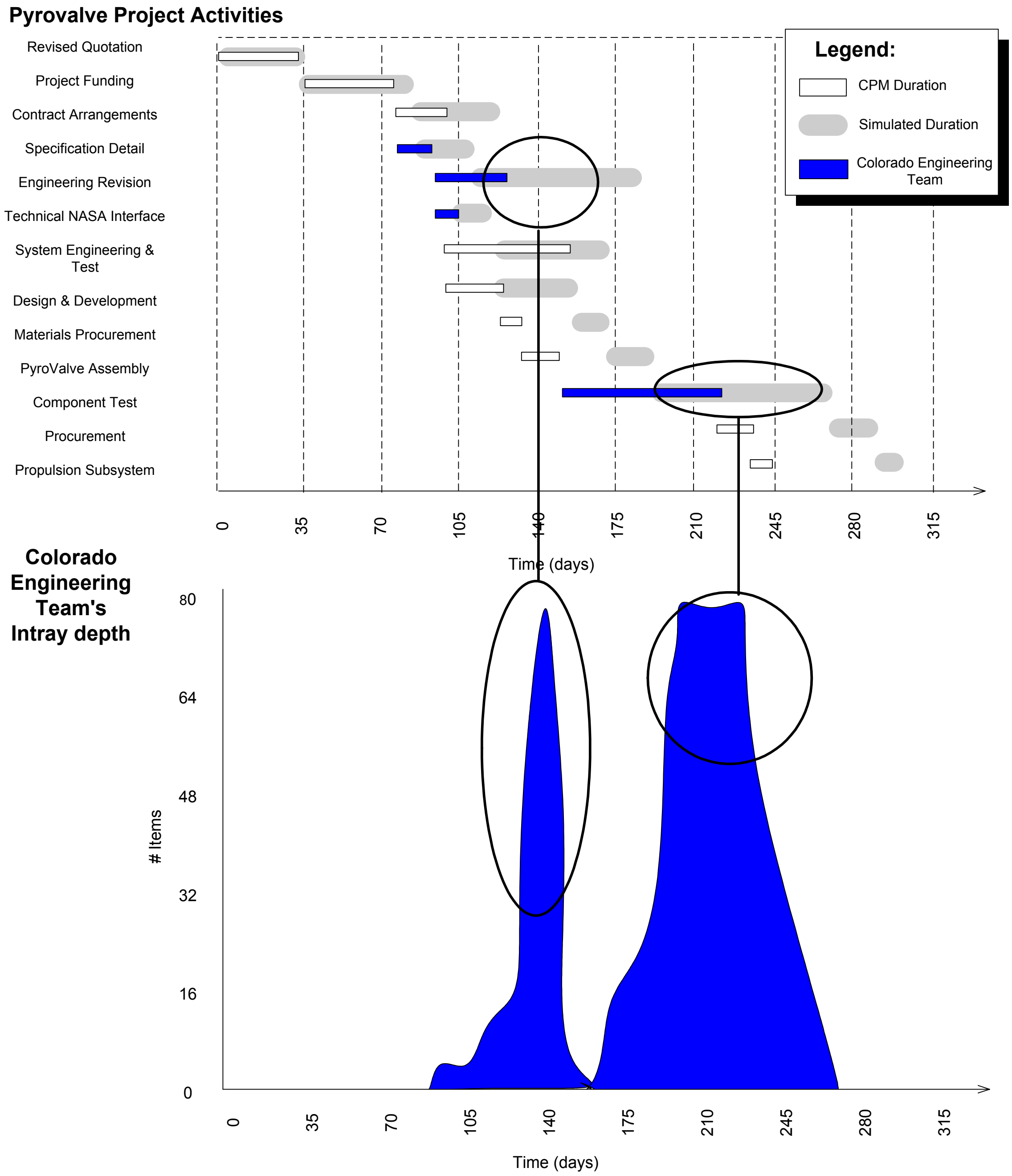

***Figure 2:* Bottlenecks and Overloads in the Case Study Model.** The top diagram is a Gantt chart of the VTA simulation. The black or white bars represent durations for each activity anticipated by the CPM. The thicker gray bar around each black or white bar represents the predicted duration of that activity in our simulation. A time-dependent project simulation considers primary work, coordination work and exception-handling work. We can see that the simulated durations of activities for the Colorado Engineering team greatly exceeded the anticipated durations. The bottom diagram depicts the simulated in-tray depths for the Colorado Engineering team. Again, we can see that the in-tray depth of the Colorado Engineering Team was exceptionally large, implying that this subteam was greatly overloaded. The linked bubble annotations connect this actor's peak backlogs to the activities for which the actor is responsible at the time of the predicted backlogs.

The cooperating project manager considered the VTA analysis to be reasonable, and he felt that it predicted real risk to the cost, schedule and quality. Considering our VTA analysis shortly after project start, the manager felt that many interventions could have proven useful, e.g., extending the planned project duration and hiring more staff, but that they would not have been feasible for this project at the time our study was performed.

In section 4.2 we presented three managerial organizational challenges. They pertained to (1) maintaining not only quality standards, but also tightened costs and duration goals, (2) building a project set of values or culture in which problems are constructively resolved in teams of different participating companies, and (3) reducing management's military-inspired propensity for high micro-management.

In light of these challenges and our initial simulation results, the cooperating manager intervened in the engineering process. He asked a team member to remind staff members informally of an existing project policy, namely, that all information requests from any project staff member to another should receive an appropriate response within 48 hours. He then sent a message to his staff asking them to report to him if ever their requests for information went unanswered beyond 48 hours. The project manager had more relevant experience than any other member of the project staff did. He offered to help when needed with a telephone call or a visit to any project participant or participants who had an information request that was not attended to and answered on time. After we questioned the manager further, the manager said that he would get on the phone or plane after 48 hours if needed. He thus threatened to *increase* his preference for micro-management. The project manager specifically asked a member of the team to observe participants' backlogs regularly and to report any problems to him.

We cannot represent this intervention directly in our information-processing model of product development teams. Consequently, to represent the intervention, we need to do an interpretation, i.e., map the real-world behavior to the simplified information-processing and decision-making behavior in our model. To make our comprehension of the intervention richer, we consider three interpretations below. These are not the only interpretations that we could make, but are those we think are most appropriate.

The project manager signaled that he might make a visit if information requests were not appropriately responded to within 48 hours. The goal of responding to every information request within 48 hours and therefore maintaining low backlogs is easily measurable. Incentives are closely related to how well the project participants meet their assigned goals. Therefore, the project participants would likely think it a failure to be contacted by the project manager regarding information-processing delays. Naturally, the project participants will try to avoid such failures. In our model, there are at least three strategies the actors use to avoid such a failure: (1) they align goals by energetically relying on project data (manifested in the Statement of Work) and thereby reducing the amount of negotiation and communication with peers to integrate diverse perspectives, (2) they reallocate attention to old communication to make sure that the older communications are taken care of first, and (3) they shift their attention allocation priorities somewhat from doing the primary work for which they are accountable to doing coordination work in order to support the information request of colleagues.

We assume that actors' actions are driven by goals, and, as a consequence, most interactions are driven by *goal incongruency* between actors. Therefore, an appropriate response of the professional project engineers would be to rely on the project manager's vast experience (manifested in the Statement of Work) and align potential goal discrepancy effectively when needed. This kind of response leads to a faster understanding and clarification of the trade-offs associated with each solution under consideration and, hence, an avoidance of lengthy discussions. Over time, it encourages actors to formalize their knowledge of these trade-offs implicitly or explicitly into a "goal trade-off table." Shared goal trade-off tables among project participants can be viewed as a common set of values or culture. The existence of shared values and culture is now widely viewed as increasing efficiency because shared values can serve as a set of guideposts or touchstones that allow actors to make decisions more quickly and consistently when similar problems arise further downstream (Kunda, 1992). In sum, one representation of the managerial intervention is that it reduces the goal incongruency between the project actors. (The process of goal alignment is exogenous to our model, but the effect of goal alignment on information-processing behavior is not).

The VTA system can be characterized as a discrete event simulator. The basic idea is that pending events (primary work, coordination work or exception-handling work) in the simulation are entered into a queue sorted by a time value that indicates when the event will occur. One by one, the global simulation controller selects events from the queue and places them in an actor's "in-tray" (to-do stack). All incoming events are stored in the in-tray, waiting for the actor's attention. Each item in an actor's in-tray has a certain priority and time of arrival. In our model, the attention allocation decision process is modeled through a probabilistic attention allocation matrix. The actor's choice of one item at a time from the in-tray is stochastically based on either priority (inferred from the type of communication and the actor's relationship to sender), time of arrival (FIFO or LIFO), or random selection. We can model redirection of attention to emphasize older communications more heavily by simply raising the attention rule probability for FIFO items in the in-tray and reducing probability for using LIFO, priority, or random attention rules.

The third potential response of the project engineers would be to shift their priorities somewhat from doing the primary work for which they are accountable to the coordination work to support the information requests of their colleagues. This can be done by (1) assigning higher priority to exceptions and communications items vs. primary work, and (2) by increasing the probability of using priority to select items from the in-tray or lower the %-attendance of responsible actors to primary work.

In the next section we demonstrate how our model can represent these interventions and predict how project efficiency as well as work process quality might be affected.

8.2 Model Predictions for the Project Team: Alternative Conditions

The guiding motivation underlying our alternative experiments was to determine the trade-offs in performance associated with intervening in the engineering process in each of the aforementioned ways. The challenge facing the project manager was to intervene in such a way that project cost and duration were minimized while quality was maintained, especially when the project manager focused on timely response to communications. Our Coordination Quality measure captures the responsiveness of actors to communications. A communication item has a lifetime after it arrives in an actor's in-tray depending on the type of communication tool through which the communication was transmitted. For example, a communication transmitted by email dies after five days if it has not been attended to. The discarded, non-attended communication will indicate that the responsiveness to communications is not in accordance with project policy.

8.2.1 Goal Alignment

Our first experimental design systematically varies goal incongruency and predicts what will happen to project efficiency and work process quality if the goal incongruency is shifted from the baseline configuration to a different level of goal incongruency (Figures 3 and 4). We specifically have indicated what would happen if the project manager's intervention caused the baseline goal incongruency to change to uniformly low goal incongruency.

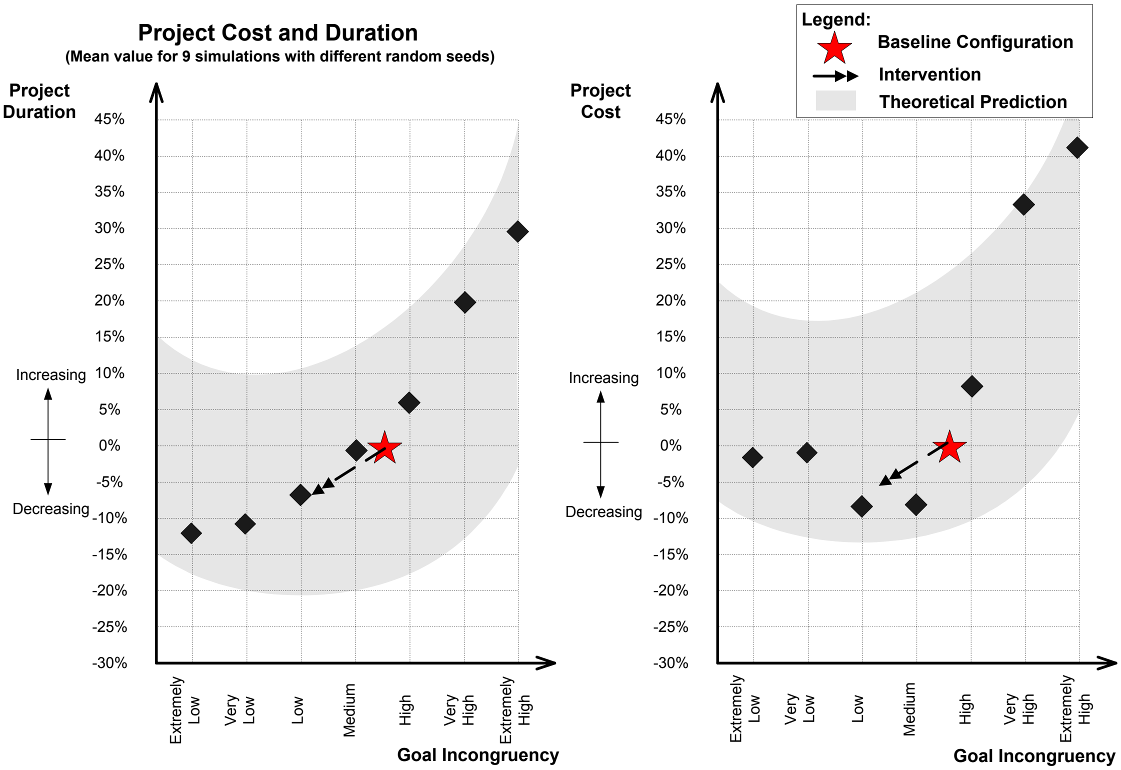

Figure 3: **Simulated Work Process Efficiency vs. Goal Incongruency**. The graphs show goal incongruency on the horizontal axes and change in project duration and cost on the vertical axes. We used the initial input model as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high. In our study, the average level of measured goal incongruency was incrementally higher than medium. To get this average project goal incongruency level, the dyads with extremely high goal incongruency were given a value of 1.0, and we gave all other goal incongruency levels a number relative to 1.0 so that the distance between the goal incongruency levels were equal. We then averaged these numbers and got the average project goal incongruency level.

The VTA simulation of our case study model showed the resulting project cost and duration curves to be concave upwards, somewhat like a flat, J-shaped function.

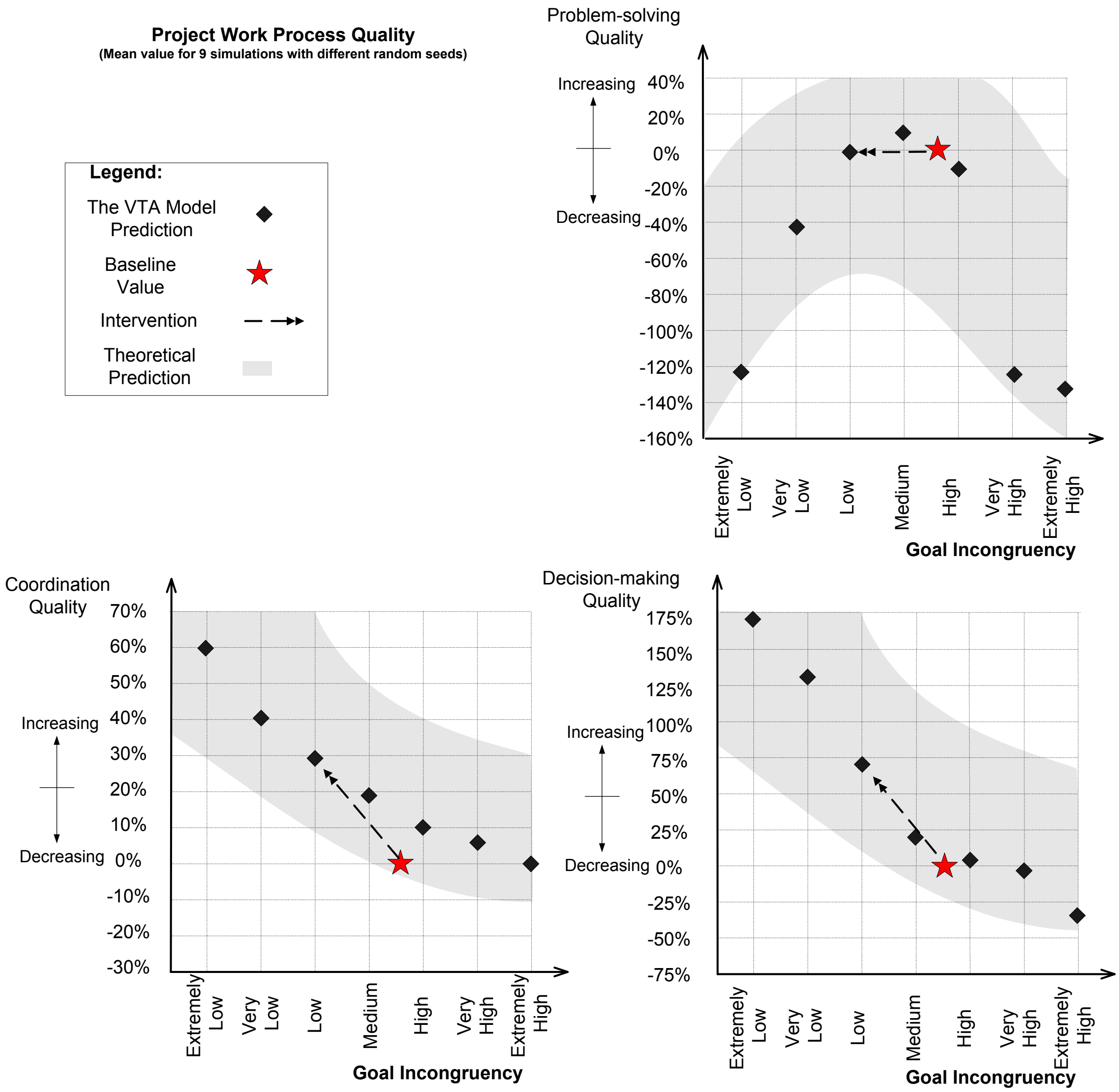

Figure 4: **Simulated Work Process Quality vs. Goal Incongruency.** The three graphs show goal incongruency on the horizontal axes, and level of work process quality for our three measures on the vertical axes. In the same way as described in Figure 3's caption, we used the initial input model as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high.

In regard to work process quality, the curve for problem-solving quality is concave downward, somewhat like a flat upside-down U. The work process coordination quality and decision-making quality curves decrease monotonically with goal incongruency.

Our simulation quantitatively suggests, and organizational theory qualitatively predicts, that for low levels of goal incongruency, the lack of diversity would cause the adoption of weaker solutions, i.e., lower problem-solving quality (Weick, 1979). On the other hand, high levels of goal incongruency would force actors to become overloaded by steamrolling and politicking communications (Pfeffer, 1981). This increase in coordination volume would force actors to become overloaded and to ignore exceptions. The preponderance of ignored exceptions would precipitate more exceptions, generated later downstream; thus, the additional rework would once again increase overall work volume, and, consequently, cause coordination quality and decision-making quality to decrease (March and Simon, 1993). Hence, moderate to low levels of goal incongruency yield the maximum level of project efficiency (cost and duration) and problem-solving quality.

The managerial implications of the results from Figures 3 and 4 are that decreasing the level of goal incongruency in the project will always increase coordination quality and decision-making quality. As our model indicates, there is a distinct trade-off to be found between efficiency vs. problem-solving quality on the one hand and between efficiency vs. coordination quality and decision-making quality on the other. In providing a quantitative measure of the magnitudes of these trade-offs, our model suggests that the manager should nurture goal incongruency at a moderate to low—but not extremely low—level. Our simulation also predicted that a moderately low level of goal incongruency reduces the number of non-responded-to communications, i.e., Coordination Quality improves. Indeed, such an intervention would significantly reduce the Colorado Engineering Team's backlog.

8.2.2 Reallocate Attention to Old Communication

Our second experimental design changed the attention focus of actors to old communications. Specifically, we raised the attention rule probability for FIFO items in the in tray to from 20% to 60%, reduced LIFO from 20% to 1%, random probability from 10% to 1%, and priority from 50% to 38%. Figure 5 shows the result of this representation of the manager's intervention.

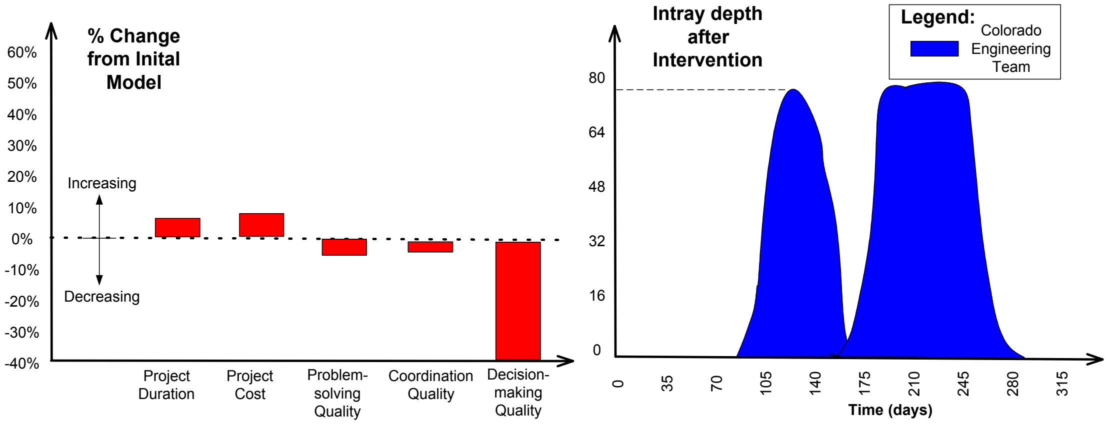

Figure 5: **The Effect of Reallocating Attention to Old Communication.** The first bar chart shows the relative change in performance indicators by representing the project manager's intervention solely as changes in attention allocation distribution. The second diagram depicts the in-tray depths for the Colorado Engineering team. We can see that the in-tray depth of the Colorado Engineering Team was increased compared to the in-tray depicted in Figure 2.

The figure clearly shows that reallocating attention to older communications does *not* improve quality, i.e., coordination quality and decision-making quality deteriorate. In addition, the project duration indicator becomes worse compared to the baseline model. This is not surprising since the critical actors (e.g., the Colorado Engineering Team) are already heavily backlogged. Redirection of attention will focus energy only on older communication, but since there are many communications, newer communications will not be attended to appropriately. The project backlog becomes worse for the Colorado engineering team compared to the baseline condition (Figure 2, especially for the large Component Test activity). This is because exceptions are not attended to, based on their high priority, as in the baseline version, i.e., decision-making quality declines. Rather, communications are attended to mostly based on arrival time in the actor's in-tray. The Colorado Engineering Team will end up being overloaded more than in the baseline case.

The implications for the manager and the professional engineers are that a greater focus on older communications results in a poorer overall performance of the project and, therefore, should not be an encouraged response.

8.2.3 Shift Priorities from Primary Work to Communication Work

In our third experimental design that attempts to represent the manager's intervention, we conjectured that the manager's intervention lowered the relative priority of primary work vs. coordination work. Further, we conjectured that one way to represent this intervention in VTA was to lower the %-attendance of responsible actors to primary work for at-risk activities by 40%, thereby giving the actors scheduled time to attend to communications.

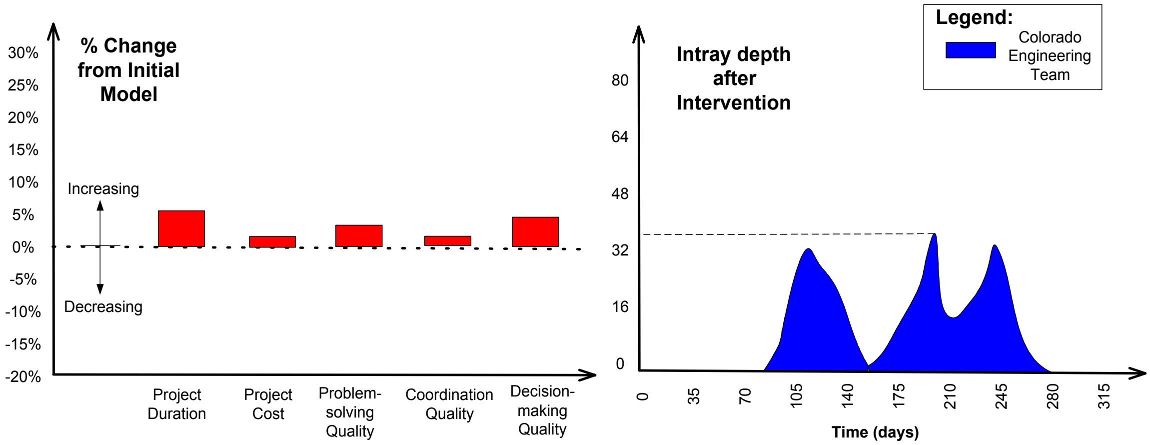

***Figure 6:* The Effect of Shifting Priorities from Primary Work to Communication Work**. The first bar chart shows the relative change in performance indicators by representing the project manager's intervention as a focus made on more coordination work instead of primary work. The second diagram depicts the in-tray depths for the Colorado Engineering team. We can see that the in-tray depth of the Colorado Engineering Team was significantly decreased compared to Figure 2.

The immediate effect of such a representation of the manager's intervention is to increase the planned work length for these activities. As a result, the responsiveness to old communication improves as well as the coordination quality and decision-making quality. It takes time to fix exceptions and attended to communications. The project cost and the project duration will probably increase. However, as shown in Figure 6, our simulation shows that this increase due to the direct effect on cost is partially offset because of a second order effect in VTA. Better-attended communications and exceptions reduce subsequent exception rates and, therefore, lead to fewer exceptions further downstream.

The implications for the manager and the professional engineers is that a strategy that focuses more on coordination work than primary work will indeed reduce the backlog and improve the responsiveness to old communications. However, there is not an acceptable reduction in cost and duration following the intervention. The project still uses about 30% more time, and the predicted budget is 10% more than the manager's CPM anticipated. Even for smaller and bigger changes in %-attendance of responsible actors to primary work for at-risk activities, the project uses significantly more time and cost than the CPM model anticipates.

8.2.4 Methodological Comments

"Calibration numbers" determine much of the actor micro-behavior in our model. The calibration numbers are located in so-called "behavior matrices." The behavior matrices contribute to, for example, the probability of generating a technical error in an activity given the complexity of an activity. The behavior matrices are used to map our real-world measures in terms of high, medium, or low ordinal values (for activity complexity, activity flexibility, etc.) into calibration numbers that we use for generating behavior probabilistically in our model. The calibration numbers we used were determined from extensive previous validation—both against organizational theory and against real-world data from different project organizations (Thomsen *et al*., 1998a; 1998b; 1998c). Obviously, the specific calibration numbers will determine the behavior in our model. The ordinal values suggest the direction, i.e., an ordinal value of high will mean a higher calibration number than an ordinal value of low. An exaggeration of differences in probabilistic numbers as ordinal values are changed from low to high should not affect the direction of our results for effect viewed alone, only the size of the effect. However, if behaviors have opposite effects, the magnitude of the calibration numbers can affect the direction of the combined effect. This is a fundamental concern in this type of model, and we have attempted to address it through extensive external validation. Conducting the same three experiments with different calibration numbers in this case led us to the same qualitative conclusions that we presented above.

8.3 Final Results

Following the managerial intervention, the project proceeded without encountering any of the predicted severe information backlog problems. It finished approximately within time and budget. Therefore, the alignment of goals seems to be the dominant behavior our actors exhibited on in the face of the managerial intervention (threat).

Our case study manager had vast technical skills and therefore could rely on his skills in the development process. Other projects may not be as fortunate to have such a skillful manager. Such projects might not benefit as much from aligning goals, but should instead invest in more discussions and negotiation to draw upon diverse professionals' perspectives. In such projects, it might well be that a focus on redirection of attention to coordination work and less of a focus on primary work would be a better strategy.

We cannot attribute the project success to the manager's intervention; however, we are encouraged by both the manager's having decided to intervene following the analysis of our model and the subsequent favorable results that accorded with our model predictions. However, we claim that the use of our predictions by the manager provides evidence of VTA's representational validity, predictive power, and its usability.

9. Discussion

The computational organizational modeling and simulation approach allowed us to capture project knowledge consistently and to develop a tool to predict project efficiency and work process quality prior to project execution. This paper focused on describing a link between an information-processing model of the case project and organizational performance. By using the VTA dynamic simulation framework, we were able to provide the cooperating project manager not only with measurable output predictions (project cost, duration, problem-solving quality, coordination quality, and decision-making quality) but also to describe variables and processes that contribute to potential performance problems. We presented our model and results to the cooperating project manager. The results predicted potential future bottlenecks in the work process, and they suggested that performance would be significantly affected by changes in goal incongruency between project participants. The manager considered our results, discussed possible corrective actions, and decided to focus on facilitating smooth and timely coordination between project participants.

Our intervention study provides direct evidence, in the form of an empirical proof, that our model can be useful in practice (Argyris, 1970; 1983). We therefore can claim that there is initial evidence to refute our null-hypothesis that different organizational designs do not affect work process quality.

Providing a computational model and method that give advice in regard to managerial organizational challenges by predicting potential project risks and, subsequently, forecasting the effects of different feasible interventions, goes beyond the scope and precision of qualitative organizational theory and traditional project management tools, such as CPM models. A manager who uses our computational organizational model can conduct “what-if” experiments that represent and differentiate between different feasible intervention strategies and decide on an intervention that provides the best trade-off in regard to cost, duration, and work process quality.

9.1 Contributions to Total Quality Management

Our contribution to TQM is our development of a conceptual framework and a computational organizational model for analyzing the quality performance of an organization that relies on the prominent information-processing view of organizations (Pfeffer, 1996, p. 70). Advocates of the TQM approach assume that TQM methods are *holistically* and *universally* beneficial for all organizations (Deming, 1982; Juran, 1992; Crosby, 1979). Based on Sitkin *et al*., (1994), our *micro-contingency* approach to total quality management and organizational design rejects this assumption and considers the specific characteristics of an organization work process, hierarchy, personnel makeup, and environment before prescribing methods to improve quality. VTA moves the focus of quality management from measuring and controlling the quality of work processes to the next level—measuring and controlling the quality of the organizations that execute work processes.

Within the TQM framework (Druckman *et al*., 1997), the definition of quality is neither precise nor consensual. Our model, however, measures and controls the quality of the organizations that design and execute work processes through the metrics of actor backlogs, problem-solving quality, coordination quality, and decision-making quality as well as project cost and duration. Improvement in one organizational performance dimension usually comes at the expense of degradation in performance of another. Modeling an organization formally in our framework allows project managers to increase their understanding of project dynamics through both process formalization and analysis of results. Our metrics provides quantitative measures to support these managerial trade-off decisions in a rigorous and repeatable manner. VTA is uniquely able to predict the impact of managerial interventions on both project efficiency and work process quality.

There have been several fruitful applications of organizational science concepts to the quality management process. For example, quality management practices have been related to issues such as strategic management (Powell, 1995). We claim that our research represents a novel and unique initiative to apply theories and methods within the field of Computational and Mathematical Organizational Theory to extend the applicability of Total Quality Management (TQM) for project-oriented work.

9.2 Contributions to Organizational Science

Organizational design, like any other design process, requires specialized and validated language, theory and modeling/analysis tools. Organizational science has provided the scientific community with language and theory that have provided valuable, but thus far only qualitative, insights into organizational design issues (e.g., Burton and Obel, 1995; Galbraith, 1973; 1977; Thompson, 1967; Tushman and Nadler, 1978).

Our contribution to organizational science lies in our creation of a model of a semi-routine, fast-paced project organization consisting of a number of professionals with partially incongruent goals working collaboratively. We implemented this model in the VTA simulation framework to help researchers and practitioners design their work processes and organizations in the same way engineers now design bridges, airplanes and semiconductors—by synthesizing, analyzing and evaluating alternative "virtual prototypes" of their organizations.

In the case study reported in this paper, we identified potential performance problems, and the manager decided to intervene proactively in the planned engineering process to prevent the problems from occurring. This prospective validation method has the advantage of providing representational validity and predictive power, and it also shows that our model is useful from a managerial perspective.

In our pursuit of learning about organizations, our computational organizational model can be viewed as an "organizational inference" model. When applied to instances—i.e., test cases—our model can be used to simulate hypothetical test case scenarios that can be treated as having an interpretive significance greater than the single test case would suggest. Simulation of hypothetical future test case scenarios create a web of inferences that provide a framework and a logic for "learning from samples of one" (March *et al*., 1991). The logic is simple: small pieces of simulation results are used to construct an inference from which a variety of possible project outcomes are generated. In this way, an understanding of the consequences of behavioral processes drawn from a single detailed case study can provide valuable guidance in organizational design (Thomsen, 1998).

9.3 Model and Method Limitations

To be amenable to analysis using our model, a project should first have relatively clear objectives. Second, project managers should understand work processes well enough so they can relate requirements to processes and assign activities to different, specialized individuals. Third, the interactions between activities must be derivable from project requirements. While these criteria do not apply to all projects or organizations, they apply well to many engineering design and product-development tasks, as well as 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 created a model of a protocol (i.e., a work process) for bone-marrow transplantation (Fridsma and Thomsen, 1997). We have also applied our model to subsea oil-production satellite development (Thomsen *et al*., 1998a).

Since our long-range research goal is to provide project managers with a theory and tools to predict project behavior and performance through the development and analysis of a simulation model, it is extremely important that the simulation model capture key aspects of a project that determine project performance. The success of predicting emergent project behavior is fundamentally contingent on the accuracy and relevance of the rules of behavior which have been posited for the system at the micro-level. The assumptions regarding the nature of the constituent elements, as well as the rules which govern their interaction, determine the extent to which the emergent behavior generated by the simulation model will agree with both theory and real-world behavior. In order to ensure that our model captures the essentials of project behavior, extensive real-world validation is necessary. In the case study in this paper, an intervention suggested by the model was applied, and the project avoided the predicted problems. However, we cannot attribute high performance to the intervention alone. The project might have done well without an intervention. Other exogenous factors might have contributed more significantly to the outcome than the intervention even if the intervention provided value.

9.4 Future Work

Our two case study observations from the aerospace industry do not make up the usual statistical sampling approach on which we can do the usual hypothesis testing and ANOVA testing. The question is, can we still learn and generalize from our two case studies? A flippant answer is that we can learn significantly more than if we had studied no projects. The more complete answer is that we can learn a good deal from one sample observation (March *et al.*, 1991). The belief that we must have huge samples to learn about human behavior and organizational performance is not necessarily valid. Human nature is not that variable in organizational settings. Simon suggests about a dozen observations to get a fairly good understanding for the range of behavior one is likely to encounter in project teams (Simon, 1997b, p. 399). We have so far applied our model to a series of three case studies (Thomsen *et al*., 1998a, 1998c) and plan to do more.

Statistical evidence of our model's efficacy will come only from a series of intervention studies done in parallel with similar studies done without intervention. Nevertheless, our model has gained credibility, if not from statistical validity, then from the fact that the project manager found it valuable in performing the intervention. Our model prospectively produced predictions consistent with the results of the manager's intervention.

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11. References Cited

Anderson, J. C., M. Rungtusanatham and R. G. Schroeder (1994), "A Theory of Quality Management Underlying the Deming Management Method," *Academy of Management Review*, 19, 472-509.

Argyris, C. (1970), *Intervention Theory and Method: A Behavioral Science View*. Reading, MA: Addision-Wesley Publishing Company.

Argyris, C. (1983), "Action Science and Intervention*," The Journal of Applied Behavioral Science*, 19(2), 115-140.

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

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

Business Week (1992), "The quality imperative. What it takes to win for the global economy," (Special Issue), October 25, 1-216.

Buchanan, B. G. and E. H. Shortliffe (Eds.) (1984), *Rule-Based Expert Systems: The MYCIN Experiments of the Stanford Heuristic Programming Project*. Addison-Wesley.

Carley, K. M. (1995), "Computational and Mathematical Organization Theory: Perspective and Directions, *Computational and Mathematical Organization Theory*, 1(1), 39-56.

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.

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.

Cohen, M. D., J. G. March and J. P. Olsen (1972), “A Garbage Can Model of Organizational Choice,” *Administrative Science Quarterly*, 17(1), 1-25.

Crosby, P. B. (1979), *Quality is Free.* New York: McGraw-Hill.

Dean Jr., J. W. and D. E. Bowen (1994), “Management Theory and Total Quality: Improving research and practice through theory development,*” Academy of Management Review*, 19, 392-418.

Davenport, T. H. (1993), *Process innovation: reengineering work through information technology*. Boston, Mass.: Harvard Business School Press.

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.

Deming, W. E. (1982), *Ouality, Productivity, and Competitive Position.* Cambridge, MA: MIT Center for Advanced Engineering Study.

Deming, W. E. (1986), *Out of the Crisis.* Cambridge, MA: MIT Center for Advanced Engineering Study.

Druckman, D., J. E. Singer and H. V. Cott (Eds.) (1997*), Enhancing Organizational Performance*. Washington DC: National Academy Press.

Eisenhardt, K. M. (1985), "Control: Organizational and Economic Approaches," *Management Science*, 2, 134-149.

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

European Foundation for Quality Management (1996), *Guidelines for Companies*. Brussels, Belgium.

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, MA: Addison-Wesley.

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

Garvin, D. A. (1988), *Managing Quality: The Strategic Competitive Edge*. New York: Free Press.

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

Gresov, C. and R. Drazin (1997), "Equifinality: Functional Equifinality in Organization Design," *Academy of Management Review*, 22(2), 403-428.

Hackman, J. R. and R. Wageman (1995), "Total Quality Management: Empirical, Conceptual, and Practical Issues," *Administrative Science Quarterly*, 40, 309-342.

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

IntelliCorp (1994*), Protalk Language Reference Version 3.1.* Publication Number: K3.1-PT1.

Ishikawa, K. (1985), *What is Total Quality Control? The Japanese Way.* Englewood Cliffs, NJ: Prentice Hall.

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.

Juran, J. M. (1974), *The Quality Control Handbook* (3rd edition). New York: McGraw-Hill.

Juran, J. M. (1992), *Juran on Quality by Design.* New York: Free Press.

Kunda, G. (1992), *Engineering Culture: Control and Commitment in High-Tech Corporation*. Philadelphia: Temple University Press.

Lawler, E. E. (1994), "Total Quality Management and Employee Involvement: Are they compatible?" *Academy of Management Executive, 8, 68-76.*

Lawler, E. E., S. A. Mohrman and G. E. Ledford (1992*), Employee Involvement and Total Quality Management*. San Francisco: Jossey-Bass.

Levitt, R. E. (1996), *Virtual Experiments and Virtual Prototypes: Extending Computational Organizational Theory and Modeling Tools*. NSF proposal IRI-9700038.

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

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

March, J. G., Sproull, L. S., and Tamuz, M. (1991). "Learning From Samples of One or Fewer." *Organizational Science*, 2(1), 1-13.

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

Mintzberg, H. (1973), *The Nature of Managerial Work*. New York: Harper and Row, Pub.

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).

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

Ouchi, W. 1979, "A Conceptual Framework for the Design of Organization Control Mechanisms," *Management Science*, 25:833-848.

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. (1994), *Competitive Advantage Through People*. Boston: Harvard Business School.

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

Powell, T. C. (1995), "Total Quality Management as Competitive Advantage: A Review and Empirical Study," *Strategic Management Journal*, 16, 15-37.

Schonberger, R. J. (1992), “Total Quality Management Cuts a Broad Swath – Through Manufacturing and Beyond,” *Organizational Dynamics*, Spring, 16-28.

Simon, H. A. (1997a), *Administrative Behavior* (3rd 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.

Sitkin, S. B., K. M. Sutcliff and R. G. Schroeder (1994), “Distinguishing Control From Learning in Total Quality Management: A Contingency perspective,” *Academy of Management Review*, 19:537-564.

Spencer, B. A. (1994), “Models of Organization and Total Quality Management: A comparison and critical evaluation,” *Academy of Management Review*, 19:446-471.

Tanguiane, A. S. (1990), *Aggregation and Representation of Preferences: Introduction to Mathematical Theory of Democracy*. New York: Springer Verlag.

Thompson, J. D. (1967), *Organizations in Action: Social Science Basis in Administrative Behavior.* 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. (1998), *The Virtual Team Alliance (VTA): Modeling the Effects of Goal Incongruency in Semi-routine, Fast-paced Project Organizations.* Unpublished Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University.

Thomsen, J., M. A. Fischer and R. E. Levitt (1998a), *The Virtual Team Alliance (VTA): An Extended Theory of Coordination in Concurrent Product Development Projects.* CIFE Working Paper #44, Stanford University.

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

Tushman, M., and D. Nadler (1978), “Information Processing as an Integrating Concept in Organizational Design,” *Academy of Management Review*, 3, 613-624.

U. S Department of Commerce (1996*), Malcolm Baldrige National Quality Award: 1996 Award Criteria*. NIST, Gaithersburg, MD.

Waldman, D. A. (1994), “The Contributions of Total Quality Management to a Theory of Work Performance,” *Academy of Management Review*, 19, 510-536.

Weick, K. E. (1979), *The Social Psychology of Organizing*. McGraw-Hill Inc.

Werkman, K. J. (1990*), Multiagent Cooperative Problem-Solving Through Negotiation and Sharing of Perspectives.* Ph.D. Dissertation, Department of Computer Science, Lehigh University.

CHAPTER V

A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations[14]

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Abstract

Validation of complex simulation models, with multiple inputs and feedback loops, is a challenging, multi-faceted problem. It has received considerable attention in the Computational Organizational Science (COS) literature. The COS literature typically calls for extensive validation and discusses some guidelines for when certain techniques are appropriate. However, reports of rigorous external model validations are limited. In this paper, we use an organizational design and analysis tool, called the Virtual Team Alliance (VTA), to illustrate that one needs to perform a series of validation steps in a predefined sequence to accomplish a comprehensive, credible validation of a computational organizational simulation model. The purpose of the VTA model is to provide managers with a tool that they can use to test "virtual prototypes" of project organizations and predict outcomes prior to actual implementation—it can therefore be described as an "emulation" system. The ultimate external validation of VTA is whether or not it is useful to managers for this purpose. VTA is useful if the model forecasts problems that will occur without organizational change, managers redesign the organization based on the model's problem predictions and suggested remediations, and the organizational risks, which the model predicted are thereby reduced. To reach this kind of ultimate external validation of usefulness, VTA has to go through a "trajectory" of different validation methods. The primary contribution of this paper is the development of an innovative validation trajectory strategy for complex computational emulation models. We present a validation trajectory that includes (1) computational synthetic experiments, (2) retrospective validation and comparison with manager's "what-if" predictions, (3) contemporaneous validation, and (4) prospective validation with intervention. We discuss in some detail how we applied VTA to two portions of an ongoing aerospace project. The VTA model made predictions about severe bottlenecks and potential quality problems for one sub-team within the two project teams but no problems for the other sub-team. These predictions were subsequently confirmed. The results of our experiments agreed with those of extant, qualitative organizational theory.

Key Words and Phrases: Contingency Theory, Computational Organizational Simulation Models, Information Processing, Intervention, Organizational Design, Validation.

1. Introduction

Computational Organizational Science (COS) has come of age, enabled by ubiquitous, low-cost desktop computers and modeling techniques from artificial intelligence. The

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COS community has produced several lucid models that have provided valuable insights into organizational phenomena (e.g., Cohen *et al.*, 1972; Huberman and Hogg, 1995; Hyatt *et al.*, 1997; Carley and Lin, 1995; Oralkan, 1996; Masuch and LaPotin; 1989; Zeggelink *et al*., 1996). However, the implications of these findings for practice have been limited because the models have been intentionally simple and abstract, and used primarily for generating new theory fragments.

The Virtual Design Team (VDT) (Cohen, 1992; Christiansen, 1993; Jin and Levitt, 1996) showed that computational organizational models could provide accurate predictions for routine, fast-paced project organizations in which all participants were assumed to have congruent goals. Building off the VDT, the Virtual Team Alliance (VTA) model extended the existing VDT information-processing model to incorporate characteristics of semi-routine, fast-paced projects, and the notion that project participants could have incongruent goals (Thomsen *et al*., 1998b). The purpose of the VTA model is to provide practitioners with a modern approach to organizational engineering of fast-paced, semi-routine project organizations. By running suites of simulations to analyze the effects of different model input variables, VTA can provide managers with predicted outcomes prior to actual implementation.

Validation of full-fledged, complex computational organizational models such as VTA, with multiple inputs and feedback loops, is a challenging problem that has received considerable attention in the COS literature (e.g., Baligh *et al*., 1994; Burton and Obel, 1995; Carley, 1997). Typically, researchers call for validation, provide useful taxonomies of computational models, and elucidate the relative benefits and drawbacks of different validation approaches. In this paper, we focus on validation of emulation models (also referred to as wind tunnel or computational organizational engineering models). Since the ultimate purpose of emulation models is to provide detailed and explicit advice to practitioners on organizational design issues, emulation models require extensive real-world validation (Carley, 1997). Following Law and Kelton (1991), we argue that validation of emulation models is not a binary issue—i.e., valid or not valid—but a matter of degree. A validation strategy encompassing multiple validation methods is necessary to give emulation models as much credibility as possible. We present an innovative emulation model validation strategy and discuss how we validated the VTA model during a three-year period using this strategy.

In the following sections of the paper, we first briefly describe the overall functionality of the VTA model to illustrate that it is a complex model and therefore that validation is a non-trivial activity. Section 3 presents four validation steps for emulation models and summarizes how we performed them on the VTA model. Having provided an overview of the validation strategy, sections 4, 5, and 6 provide a detailed illustration of how we performed contemporaneous validation. Section 4 describes two portions of a real-world launch vehicle development project that we used as a test case. Based on organizational theory and our case project managers' challenges, section 5 develops detailed hypotheses that guide a set of “virtual experiments” carried out on the model of the case study with the VTA framework, as described in section 6. We conclude our paper with a summary of our practical and theoretical contributions to COS, our validation strategy’s limitations, and suggestions for future work.

2. The Virtual Team Alliance (VTA) Model

In a companion paper, "The Virtual Team Alliance (VTA): Extending Galbraith's Information-processing Model to Account for Goal Incongruency" (Thomsen *et al*., 1998b), we describe in detail the workings of the VTA model and their internal validation. This section provides the reader with an overview of that only.

VTA extends existing contingency theory (Thompson, 1967) and Galbraith’s information-processing theory (Galbraith, 1973, 1977). Galbraith and other contingency theorists focus on organizational behavior at the level of the entire organization and do not concern themselves with the internal dynamics of the organization. We have extended contingency theory to develop a micro-contingency model of goal incongruency and organizational behavior within a broader information-processing framework. This model uses actors and the relationships between pairs of actors as the fundamental units of analysis.

Within the larger framework provided by Galbraith’s information-processing model, VTA incorporates and operationalizes qualitative organizational theories that describe behavior at the level of individual actors and relationships. These theories cover the behavior of actors embedded in vertical dyadic relationships in the organizational hierarchy as well as the behavior of peer actors working on interdependent tasks. We depict organizational actors as relatively simple, goal-oriented, information processors and communicators with finite or "boundedly rational" capacity (March and Simon, 1993). Their work is choreographed by

- relatively abstract, flexible, sequentially and reciprocally interdependent information-processing activities assigned to them (Thompson, 1967), and
- organizational structures that handle exceptions from pre-planned activities reactively in the spirit of Galbraith (1973, 1977) and that proactively monitor the behavior of subordinates (Ouchi, 1979; Eisenhardt, 1985).

Exceptions are unexpected results that occur (1) during the process of product development, which overwhelm the cognitive capacity of the responsible team member (Galbraith, 1977) or (2) when an actor makes a decision about an engineering process that deviates from the usual process. We distinguish between three types of exceptions: technical errors, productive non-conformances, and counterproductive non-conformances. Technical errors are always detrimental to the product quality or successful completion of the desired objective and must be corrected to ensure the reliability and functionality of the product. Productive non-conformances are beneficial non-conformances that represent acceptable technical solutions that are superior to those anticipated by the manager or the project plan, i.e., they achieve a more desirable trade-off among project goals in terms of cost and duration. Counterproductive non-conformances represent alternative satisfactory technical solutions that are inferior to those anticipated by the manager or the project plan in terms of cost and duration.

There are two communication processes modeled and simulated in the VTA model: exception generation and information exchange. We also modeled two kinds of decision-making: attention allocation and whether or not to do rework when an exception is detected. We model seven "canonical" micro-interaction processes between actors using these two communication and decision-making processes: three interaction processes for vertical relationships—monitoring, selective delegation of authority, and exception generation—and four for lateral relationships—steamrolling, politicking, searching for alternatives, and clarification of goals. Steamrolling and politicking entail more counterproductive non-conformances, whereas searching for alternatives and goal clarification entail more productive non-conformances. The relative proportion of steamrolling and politicking behavior to searching for alternatives and goal clarification will be greater at higher levels of goal incongruency than at lower levels (Pfeffer, 1981). As more "productive" ideas are generated, problem-solving quality increases, and as more "counterproductive" ideas are generated, problem-solving quality decreases.

The total information-processing capacity of an organization is given by the aggregate information-processing capacities of its actors, mediated by the efficiency of the communication network that connects the actors together. The total information-processing "load" on the organization is derived from the project requirements, which must be met.

In this information-processing view, organizational performance emerges as a product of the fit between the load on the organization and the organization's capacity to handle that load (Tushman and Nadler, 1978). Specifically, VTA produces two measures of efficiency—project duration and total salary cost—and three measures of work process quality: problem-solving quality, coordination quality, and decision-making quality. In addition to providing a project manager with measures to support complex organizational design decisions involving trade-offs between cost, duration, and work process quality, VTA predicts risks that might adversely affect project performance. Users can identify and test feasible and useful interventions to mitigate the risks that have been identified.

3. Testing and Validation of Emulation Models

In this section, we first distinguish between testing and validation. We argue that an emulation model can be divided into three components and that each component needs validation. The section then presents four validation methods that comprise a comprehensive and credible validation strategy of emulation models. We conclude this section arguing that our validation strategy can be conceptualized as a "trajectory" in two-dimensional space spanned by "emulation model components" and "validity types."

3.1 Testing versus Validation

We use the following definitions to distinguish between testing and validation. Testing, often referred to as "internal validation," is the process of establishing that the computer implementation of the model is error-free and that the computer implementation is a correct representation of the logical behavior of the conceptual model built by the analyst. Testing is not concerned with the process of establishing whether the conceptual model is a reasonable representation of the phenomena of interest. The latter process is validation (Cohen, 1995). In this paper, we focus on discussing validation methods for emulation models.

3.2 Emulation Model Components and Their Validation

In constructing computational organizational models, researchers must balance between simplicity and veridicality (Burton and Obel, 1995). The balance point depends on the purpose of the model. The higher the asserted veridicality, the greater the need for in-depth and higher levels of validation (Carley, 1997).

In order to discuss validation, we define an emulation model as consisting of three major parts. All three parts must be validated through rigorous, clearly defined procedures.

(1) An *input model* describes the organization in question through established variables. It is impossible and unattractive to represent the real world in its entirety. Based on the questions one wants to investigate, one extracts and simplifies the most important aspects of reality. The problem being investigated suggests a sufficient, but not comprehensive, representation of the real world for the phenomena being studied.

(2) A *reasoning model* includes the simulation. The parameter representation of the input model is linked to reasoning or behavior in the simulation model. The behavior in the simulation model is, of course, less complex than the real world. It is created at level which is neither so complex that the model becomes ponderous and inefficient, nor so abstract and simplistic that the model produces no practical insights.

(3) An *output model* provides the results of the simulation. The simulation model behavior determines the emergent output. The difference between the actual project

outcome and the simulated project outcome is a measure of how accurate the computational model is in running simulations and making performance predictions.

Emulation models typically represent micro-organizational attributes in some detail (e.g., activity uncertainty in VTA). In all modeling enterprises, it is imperative that precautions are taken to ensure that any given model remains undistorted by inter-rater biases or variations in procedure on the part of the modeler. Input data are subject to strong biases that reflect the personal background of the modeler. For example, the modeler may lack sufficient domain-specific expertise to correctly identify and interpret all relevant data pertaining to the organization and its work processes. Whenever possible, we attempted to derive input data using a formalized methodology, e.g., activity complexity, activity interdependence strength, and goal incongruency in VTA (Thomsen *et al.*, 1998a). The methodology nevertheless requires some skill and judgement. In this case, the methodology for generating input itself requires validation. We employed the kind of inter-rater validity checks used by social scientists who design and test survey instruments to ensure that the input data is valid (e.g., Babbie, 1995).

For semi-routine, fast-paced project organizations, behavioral micro-processes are relatively well understood, but the complexity of their interaction overwhelms closed-form mathematical solution approaches. Indeed, emulation models are necessitated by the inability of the human mind to extrapolate from understanding of canonical micro-processes to predictions regarding the emergent effects of these processes in a non-linear, complex web of relationships. The approach in VTA was to use, as far as possible, widely accepted or canonical micro-behaviors of actors (monitoring, selective delegation of authority, exception generation, searching for alternatives, goal clarification, steamrolling, and politicking). We relied on economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior (Thomsen *et al.*, 1998b). When theories were lacking, we gathered our own empirical data to validate the behavior we chose to implement.

If the input data is inter-rater validated, and canonical micro-behaviors are validated in the extant literature or through new observations, then we are ready to compare the emergent behavior of the model against qualitative predictions from macro-organizational theory and real-world data. This is an extremely challenging task that requires a variety of validation methods. We used (1) computational synthetic experiments, (2) retrospective validation and comparison with manager's "what-if" predictions, (3) contemporaneous validation, and (4) prospective validation with interventions.

The next sub-section summarizes these approaches, and section 4, 5, and 6 provide a detailed description of how we conducted contemporaneous validation on a project that developed a new launch vehicle for bringing satellites into space.

3.3 Validation Methods

A number of valuable validation methods has been proposed in the COS literature, such as grounding, calibrating, verification, and harmonization (e.g., Carley, 1997). Based on the emulation model purposes, we supplement these validation methods with four methods that we think are necessary to move emulation models from being useful to researchers to being useful in the realm of practitioners as well.

3.3.1 Computational Synthetic Experiments

We applied VTA to a number of small synthetic test cases—"toy" organizations—simple enough models that they could be analyzed manually. Based on the actor and activity micro-behavioral assumptions, we could adjust the model until its micro- and macro-predictions were consistent with our expectations. This method has the advantage of being relatively easy to perform, but is limited in that it does not necessarily relate to realistic large-scale test cases. The purpose is first to calibrate the micro-behavior of the model for the toy problem against the micro-theoretical predictions. Second, we want to validate the emergent macro-behavior of the model according to the predictions of established organizational macro-theory, and to understand which model variables were dominant and how they interacted (Thomsen *et al.*, 1998b).

3.3.2 Retrospective Validation and Comparison with Manager's "What-if" Predictions

We calibrated the internal variables of VTA against past data from a completed project. After adjusting VTA calibration parameters to reflect past project outcome data, we were able to reproduce the actual project outcomes. Then we applied VTA retrospectively to another completed real-world test case. We compared the simulated model predictions with the actual project outcome. Thereafter, we asked the project manager to make predictions about the effect of hypothetical changes to key input variables in the project's initial configuration (actor's skill set and goal incongruency between actors) on dependent measures of time, cost, and process quality. We compared our simulated model predictions with the project's actual outcome as well as with those of the manager's "what-if" scenarios. We ran t-tests on the data to show that the manager's prediction and the simulation results were statistically consistent.

Since VTA is an operationalization of qualitative organizational theory, the aggregate predictions of the model about the effect on a dependent variable (e.g., duration) caused by a change in a relevant input variable (e.g., actor-activity skill match) can be tested qualitatively against the predictions of the textual theory as well. VTA simulation results agreed qualitatively with this macro-organizational theory. This validation method has the advantage of relating to test cases of realistic scale, but it provides no evidence that the modeling method can be used in practice to support organizational design decisions. The ability to capture salient features of a realistic project and calibrate the values of model attributes demonstrates representational validity. Retrospective validation also provides insights into the cause-and-effect relationship between different calibration parameters and project performance (Thomsen *et al.*, 1998a).

3.3.3 Contemporaneous Validation

We applied our model to two on-going, real-world test cases and performed a series of experiments that produced forward predictions about the remaining project outcomes. These predictions agreed qualitatively with organizational theory. This method is more robust in that the researcher cannot "curve fit" calibration parameters to unknown future performance benchmarks. Rather, at the end of the project, we retrospectively compared the project's final results to the VTA's previously predicted results. Both VTA predictions about aggregate dependent variables (e.g., cost) and micro-dependent variables (e.g., actors' "in-tray depth") results agreed relatively closely with the actual project result. Thus, the study provided evidence not only about the representational validity of our model but also about its predictive power. From a managerial perspective, however, the value of contemporaneous modeling is limited, because it is more difficult to initiate interventions and mitigate risks in an ongoing project than to do this at the outset of a project. An application of the contemporaneous validation method is provided in section 4, 5, and 6.

3.3.4 Prospective Validation with Interventions

In the last of our case studies, we modeled the planned work process and organization and prospectively identified potential project performance problems. After considering our recommendations, the cooperating manager intervened in the engineering process to reduce some of the organizational risks that the model had predicted might adversely affect project performance. The manager had developed confidence in the validity of the VTA modeling approach and tools based on the accuracy of our predictions in the contemporaneous test case. In our subsequent observations of the project, the potential risks that our model initially identified as being likely to affect project performance adversely were avoided by this intervention. This prospective validation method has the advantage of providing representational validity and predictive power. Moreover, it demonstrates that our model could have significant value from a managerial perspective. We can thus claim that we have evidence of VTA's usefulness for practitioners (Thomsen *et al*., 1998c).

3.4 Suggested Validation Trajectory for Emulation Models

To validate an emulation model against its ultimate purpose of providing practitioners with guidance in organizational design decisions, we used four validation methods. Even though the validation methods are autonomous, there is a conjunctive relationship among them. We argue that inter-rater validity checks on model inputs, computational synthetic experiments, retrospective validation and comparison with manager's "what-if" predictions, contemporaneous validation, and prospective validation with interventions are all essential building blocks in a comprehensive validation strategy for emulation models and have a logical sequence. That is, the input to emulation models has to be validated before the behavior within the model: "Garbage in leads to garbage out." The model behavior needs to be validated before the output can be validated: "Learn how to stand before walking." Finally, it is necessary to triangulate the resulting simulated outputs against predictions of macro-organizational theory and real-world data to make sure that the dynamics of the simulation model are valid—a "three-legged stool" validation approach.

Retrospective, contemporaneous and prospective validation form a hierarchy of stringency and difficulty in terms of external validation of the usefulness and credibility of emulation models. Prospective validation provides evidence that the model is useful for practitioners. Predictive power is a prerequisite for usefulness. Having predictive power guarantees representational validity. It is important to note that the validation strategy we have suggested here is a joint approach that simultaneously addresses the validity of the inner workings of the model and the results that it generates. An effective emulation model provides practitioners with measurable output predictions (e.g., project cost and duration). It also predicts factors or processes that contribute to potential performance problems and recommends possible corrective actions through virtual experiments. The internal workings of the emulation model must be rich, observable, and validated to represent relevant real-world organizational behavior.

Our validation strategy for the VTA model was to tackle the less challenging retrospective validation before contemporaneous validation and prospective validation. Contemporaneous validation and prospective validation requires that the practitioners have some confidence in the emulation model from previous validation efforts. If not, the practitioners will not be willing to base interventions on the emulation model's recommendations (Argyris, 1970; 1983).

Figure 1 depicts how we conducted the VTA validations and the validation trajectory strategy we propose for organizational emulation models.

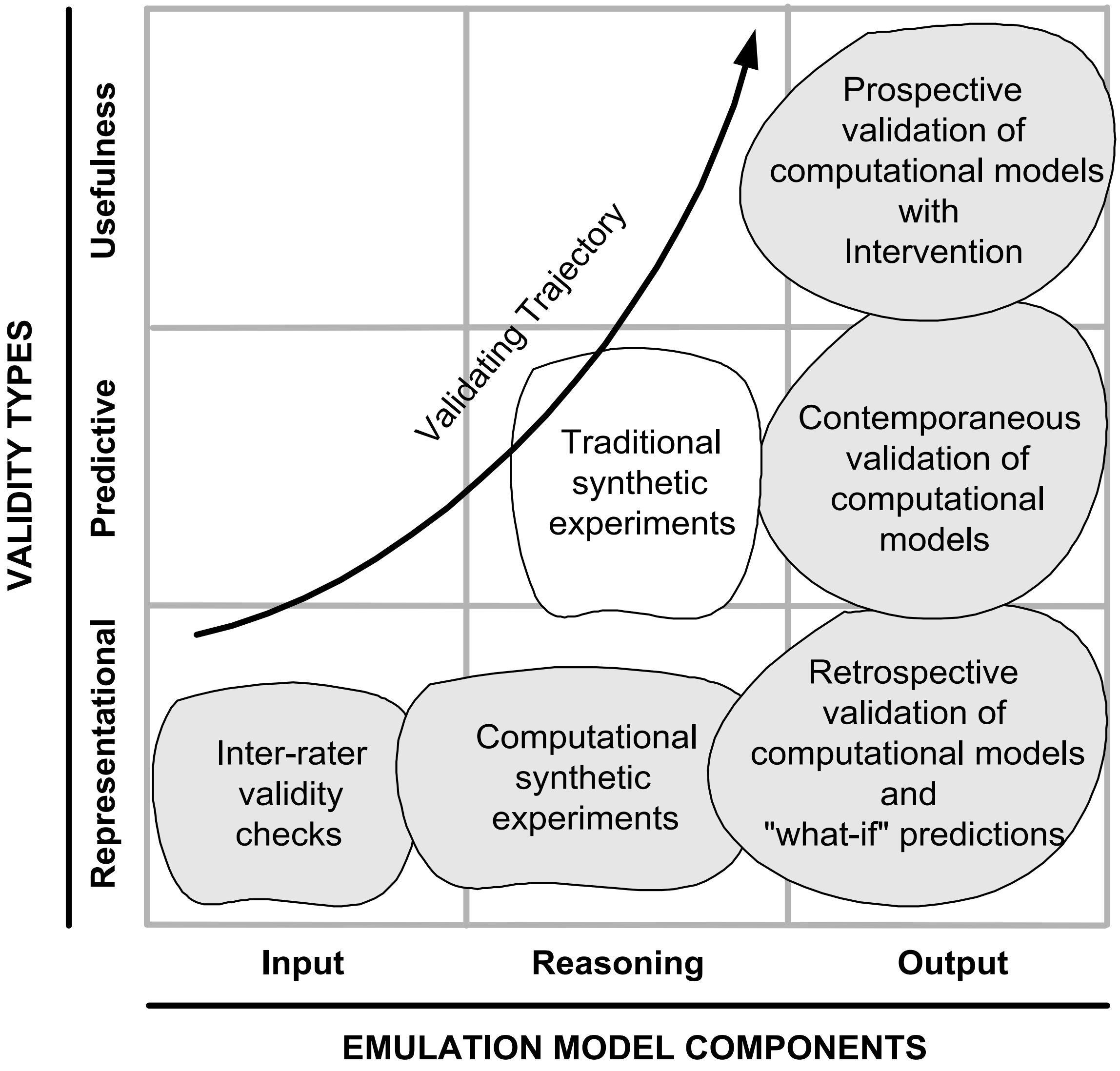

Figure 1: **Trajectory for Validating Emulation Models.** The figure depicts the validation strategy we performed during a three-year period on the VTA model. We propose that this strategy is broadly applicable for emulation models that aim at providing managers and researchers with capabilities to test virtual organization prototypes and run virtual organizational experiments. In addition to the trajectory of validation steps we performed for the VTA model, traditional Social Science, "synthetic experiments" involving groups of paid subjects might be valuable extensions to field observations or computational synthetic experiments in the course of validating areas of micro-behavior in emulation models that are not yet "canonical."

4. Launch Vehicle Development—A Case Study

This section first describes the research setting at our collaborating company, and reports on our case-study data collection approach. Following this, we describe organizational managerial challenges facing our collaborating partner and how the VTA emulation model was able to provide practical advice to our cooperating manager regarding his organizational challenges

4.1 Research Setting

We have taken our case study from a company within the aerospace industry that has traditionally developed launch vehicles for military applications. However, in light of the recent reductions in U.S. military spending and the company's entry into the commercial market, the main issue for the company today is to remain economically competitive by shrinking the time-to-market and cost of new products and by maintaining reliability. The introduction of the new launch vehicle program in 1993 marked a major milestone in the effort to build a commercially viable, versatile, and reliable spacecraft that could provide customers with quick access to space by minimizing preparation time before launch. The launch vehicle program is made up of various Product Development Teams (PDTs). We modeled two key PDTs, Avionics and Structures.

The first project team for which we created a model was the Avionics Product Development Team. The Avionics PDT was responsible for designing the electronic systems that supported such functions as guidance, telemetry, and destruct for the launch vehicle as well as for the various interconnections that link these functional systems to the rest of the vehicle and to each other. These systems were packaged in the form of flight boxes and were housed within the Equipment Section of the vehicle. The primary task of the Avionics PDT was to design and produce those flight boxes that were to be developed internally, to procure those flight boxes that were to be acquired externally, and to design and produce the cabling and interfaces. Cabling and interfaces were necessary to connect the flight boxes to each other and to other subsystems of the vehicle.

Avionics project participants were highly skilled specialists apportioned to the project by discipline-oriented home departments. They were divided into sub-teams according to function. The Avionics project manager was comfortable delegating authority and refrained from micro-management. Project participants responsible for activities were given great autonomy to come up with solutions to activity requirements. The development of new flight boxes is a highly complex process, requiring numerous iterations and extensive coordination. Product developers who used CAD systems for design tasks had to exchange information with all other sub-teams that interfaced with their particular flight box in order to produce a design that would meet shared requirements properly. For example, it was incumbent upon the designers of a flight box to communicate with the Cables sub-team in determining the type and location for all connections. Figure 2 shows our model of the Avionics PDT.

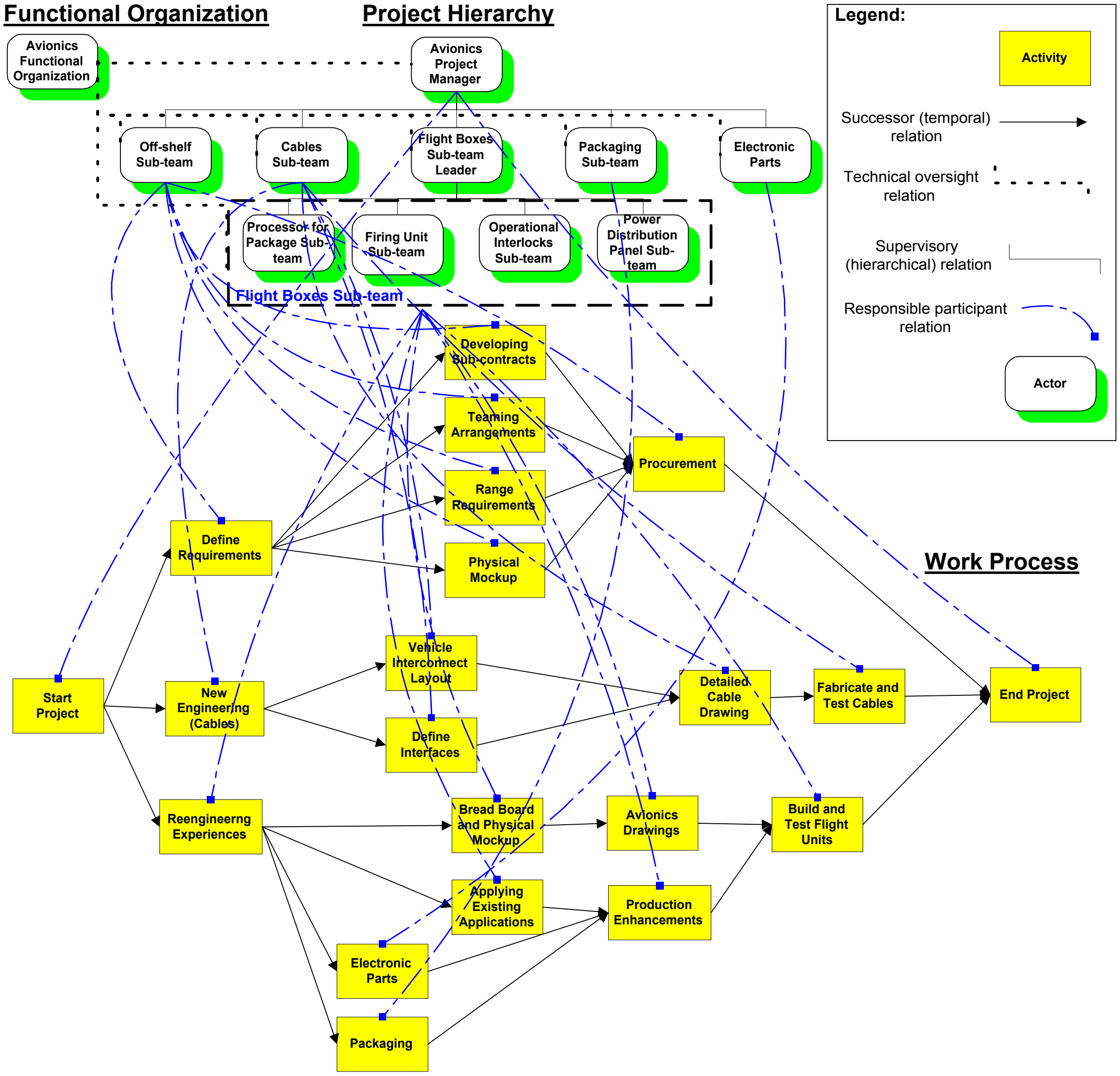

***Figure 2*: The Avionics Development Project Work Process and Organizational Hierarchy.** In our conceptual model, a project has two building blocks—the actors (embedded in an hierarchical organizational structure) and the activities (the Critical Path Model (CPM)). That is, each actor fills a position in the organizational hierarchy and works on one or more activities; the organizational structure and the interdependence between activities define relationships between actors. Avionics has a matrix structure in which subordinates report to two supervisors at the same time—one supervisor responsible for the project, and one responsible for a particular functional discipline. To incorporate this influence of functional managers in our model, we represent functional managers explicitly as actors.

The second project team for which we created a model was the Structures PDT. The Structures PDT was responsible for the development of the overall physical structure of the launch vehicle and the various structural components, which constitute the general framework for the vehicle.

The members of the Structures PDT were highly skilled professionals. The project manager served in a dual capacity as the Structures PDT leader and as the leader for the structural design functional group. The Structures project manager was not comfortable delegating authority and engaged in micro-management. The Structures PDT activities were highly specified and therefore gave very little flexibility to the responsible actors.

The Avionics and Structures PDTs differ considerably on a number of important dimensions. The Avionics PDT is characterized by high level of interdependence between activities, high activity flexibility, high level of goal incongruency, and a low preference for micro involvement by the Avionics project manager. Following March (1991), we refer to this as an "exploratory" project team. In contrast, the Structures PDT is characterized by a low level of interdependence between activities, a low level of activity flexibility, low level of goal incongruency, and a high preference for micro-involvement by the Structures project manager. We refer to this as an "exploitative" project team.

4.2 Data Collection

We obtained data on the organizations through semi-structured interviews with key project members, which we then used to construct the models in conjunction with continuous input from project participants. We conducted roughly forty interviews in the period from January 1995 to February 1997. Most interviews were tape-recorded and transcribed. We conducted interviews with project participants at all levels of the hierarchy, ranging from the vice-president responsible for the entire division (of which the launch vehicle program was but one element) down to individual project designers. Project team leaders were typically consulted on a bi-weekly basis to evaluate our results. When the input representation of the project was completed, our research to that point was presented in a technical report (Thomsen and Kwon, 1996) that received verification from the project managers. Later simulation results were also discussed with other project managers in order to validate the inputs and behavior of our model (Thomsen *et al.*, 1996). Before conducting virtual experiments, we asked managers for simple predictions, and examined whether our model generated results comparable to those predicted by the managers.

4.3 Managerial Organizational Challenges

Two main organizational challenges faced the Structures and Avionics development team project managers:

1. The launch vehicle program was assembled from multiple participating organizations, and consisted of multiple constituent sub-teams. The participants inevitably include members whose goals differ not only within the team, but also across teams. Project teams need to work unencumbered by close managerial scrutiny, highly formalized detailed plans, supervisory approvals and other "bureaucratic delays." Work autonomy or flexibility is needed to meet aggressive cost and duration goals. However, cost overruns and missed deadlines might be the result if there is too much goal incongruency between interdependent actors in the face of activity flexibility. The specific question that the project manager had to consider was the following: *What level of goal incongruency should I encourage so that: (1) task interdependencies can be worked out, (2) issues involving technical trade-offs between various perspectives can be resolved, and (3) solutions and approaches that build upon the diversity of relevant expertise and perspectives can all be determined?*
2. The earlier, military-related focus on product performance at virtually any price has been replaced by a focus on product cost-effectiveness and timeliness as the most important organizational goals for our cooperating aerospace company. These three drivers (cost, schedule, and quality) are not independent variables. Given the cost-schedule-quality priority for the launch vehicle, the design approach is very sensitive to cost, and must allow capability within cost and schedule to define the required quality. Quality requirements and cost-driven capabilities must find a middle ground where adequate quality can be achieved for a reasonable cost. However, most of the project participants have gone through extensive education and training in classified military product development projects, becoming steeped in the product performance *Weltanschauung* of such programs. The specific question that the project manager had to consider was the following: *Which participants do I allocate to activities to:*

(1) create a collaborative, innovative project environment, and (2) to increase the likelihood that the team will meet not only quality standards, but also tightened cost and duration goals?

Neither Critical Path Models (CPM) nor VDT can give practical answers to these questions. CPM (Moder *et al*., 1983) project scheduling tools ignore coordination and rework, and VDT (Jin and Levitt, 1996) ignores goal incongruency between professionals from multiple disciplines. Our VTA model is an attempt to bridge this gap by providing a tool for developing theory and analysis tools to allow project managers to balance organizational design and management policies in such a way that optimum performance is achieved for a given level of goal incongruency.

5. Hypotheses

VTA can be thought of as a hypothesis-testing machine. Since we are focusing on validation in this paper and the managerial challenges are related to goal incongruency, this section will generate a number of hypotheses in regard to goal incongruency.

Deriving specific, testable and interesting hypotheses from organizational theory is not easy. Organizational science tends to be qualitative, descriptive and aggregate. Thus, even qualitative predictions may require interpretation and balance of conflicting theoretical arguments (Burton and Obel, 1995). The body of theoretical research described in a companion paper (Thomsen *et al*., 1998b) supports the following hypotheses.

Hypothesis 1 (H1): ***Problem-solving quality****, the ratio between (productive non-conformances minus technical errors and counterproductive non-conformances) to (total number of exceptions), will peak at moderate levels of goal incongruency and drop at both lower and higher levels.*

Higher goal incongruency leads to more problem-solving communications. Because of the limited information-processing capacity of actors, a high number of communications will result in more non-attended communications (Simon, 1997). Non-attended communications are communications that are not processed because of negligence or overload on the part of the actor responsible for processing the communication. However, a very high level of goal incongruency may lead to a collapse in communication and ultimately to phenomena known as steamrolling and politicking (Pfeffer, 1981; Thomsen *et al*., 1998b). Non-attended communications lead to breakdowns in coordination, since important requests for information may not be heeded, or vital information may not be received. Therefore, the more communications that are attended to, the lower the probability that misunderstandings or lack of information will degrade the coordination quality of the project.

Hypothesis 2 (H2): ***Coordination quality****, measured in terms of the number of attended communications divided by the total number of communications, will monotonically decrease with increasing goal incongruency in a relatively linear fashion.*

Typically, higher levels of goal incongruency cause more communications and more exceptions to be generated on the project. Because of limited information-processing capacity of supervisors, more default delegations will occur. Default delegations represent exceptions which are decided upon by an inappropriate actor due to the lack of timely decision-making about the exception by the appropriate actor. Each undetected exception represents a failure of the organizational members' ability to monitor their own behavior. A low proportion of detected exceptions to total exceptions indicates that the existing exception detection and handling system is flawed.

Hypothesis 3 (H3): ***Decision-making quality****, measured in terms of the ratio of the number of exceptions decided upon by the appropriate personnel in a timely manner to total number of exceptions, will monotonically decrease with increasing goal incongruency in a relatively linear fashion.*

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 will therefore improve project performance, e.g., reduce project duration and cost (Weick, 1979). At the same time, organizational theory indicates that too much goal incongruency can lead to time-consuming arguments and undermine project performance, i.e., increase project duration and cost (March and Simon, 1993).

Hypothesis 4 (H4): ***Project duration****, measured in terms of the total time required for the project to be completed successfully, will vary as a concave upwards U-shaped function with goal incongruency.*

Hypothesis 5 (H5): ***Project cost****, measured in terms of the total work volume generated by the project, will vary as a concave upwards U-shaped function with goal incongruency.*

Goal incongruency between two peer actors will have a direct effect on actor behaviors only if they are reciprocally interdependent (Thompson, 1967). If the work of one of two peer actors were completely independent of the work of the other, the actors' incongruent goals would be inconsequential. Two incongruent actors are more likely to desire different solutions if the solution space is large (i.e., high activity flexibility), since each actor has a greater probability of finding a solution which differentially meets his or her particular preferences.

Hypothesis 6 (H6): The effects of goal incongruency on all project performance indicators should increase with increasing levels of activity flexibility and interdependence between activities.

The next section presents and discusses a computational experiment that tests our hypotheses and provides the cooperating project managers with insights into their organizational challenges.

6. Computational Experiments and Results

The primary purpose of our experimentation program was to: (1) test our hypotheses (section 5) regarding the effect of goal incongruency between organizational actors on project team performance, (2) provide an illustration and evidence of how our model can be used to predict project schedule, process quality and cost risks, and (3) to provide the cooperating project management with guidance in relation to their managerial challenges.

Our simulation results from the Avionics and Structures models can be divided into two categories. The first set of results involves the straightforward predictions made by our model regarding the future behavior and performance of the actual project. The second set of results pertains to the data we obtained from a series of what-if experiments, in which our model predicted the likely performance of the project teams.

6.1 Model Predictions for the Project Teams: Initial Conditions

The dynamic VTA simulation of the information-processing behavior of our model for the Structures PDT did not predict any significant deviation from the original project plan or from the anticipated performance of the project. However, the model for the Avionics PDT predicted a severe risk of coordination bottlenecks within two of its subteams, the Cables Subteam (Figure 3) and the Flight Boxes Subteam, that represent risks of significant increasing time and cost for the project. Of the two cases, the overload on the Cables Subteam was greater.

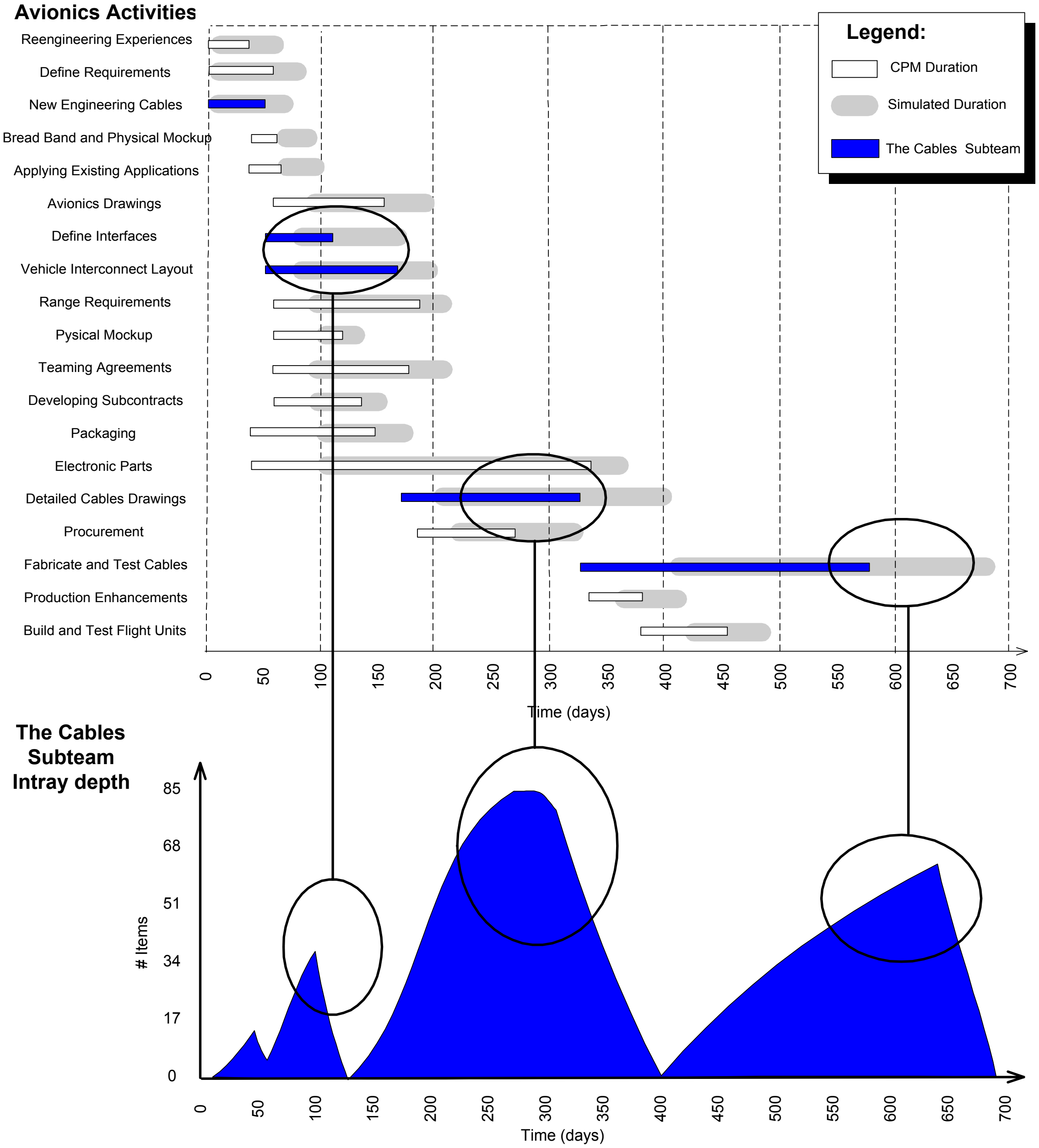

Figure 3: **Bottlenecks and Overloads in the Avionics PDT.** The top diagram is a Gantt chart of the Avionics PDT simulation. The thin black or white bars represent durations for each activity anticipated by the CPM, and the thicker, shaded bar overlaid on each thin bar represents the predicted duration in our simulation. We can see that the simulated activity durations by the Cables Subteam greatly exceeded the anticipated durations. The bottom diagram depicts the predicted in-tray depths for the Cables subteam. We can, again, see that the in-tray depth of the Cables Subteam was exceptionally large and that this subteam was greatly overloaded.

The manager for the launch vehicle program project considered our VTA analysis to be reasonable, and he felt that it predicted real risk to the cost, schedule and quality. Since the severe backlog occurred in an external team developing an outsourced component of the avionics package, there was a limited range of feasible interventions for this project at the time our study was performed.

In light of the managerial organizational challenges (section 4.3) and our simulation results, an appropriate managerial intervention could be to ensure that professional project engineers aligned their goals to those of the project and to each other. With lower goal incongruency, actors would need fewer communications to integrate their diverse perspectives and they could devote more attention to the primary work for which they were accountable. There are at least three ways to accomplish such an intervention:

- **Reduce use of outside subcontracts**: In the traditional procurement procedures of our cooperating partner, most parts were fabricated internally. However, substantially faster implementation than previously achieved with comparable military launch vehicles necessitated that parts were procured following an open bidding process. Such “make-or-buy” decisions had historically resulted in a “make” decision. Because of heightened cost pressures in our case study, much work was outsourced to external component suppliers whose goals were incongruent with those of the prime contractor. An option for the project manager could therefore be to reverse the “buy” decision and instead choose to “make.”
- **Increase micro-management**: The project manager had more relevant technical experience (he had 15 previous years experience as a rocket scientist) than any other member of the project staff. He could, therefore, also offer to help when needed with a telephone call or a visit to any project participant or participants who struggled to find a trade-off solution to a number of concurrent desired goals.
- **Introduce "inside" and "outside" incentives**: The project manager could attempt to incentivize "inside" project participants (from the same organization) to emphasize the manager’s goals through performance appraisals. Outside subcontractors' goals could be regulated through contractual arrangements—e.g., by use of incentives for critical performance metrics in vendor contracts.

In the next section, we demonstrate how our model can represent such goal-alignment interventions and can predict how project performance as well as work process quality might be affected.

6.2 Model Predictions for the Project Teams: Hypothetical Conditions

Prior to conducting the computational experiment (Figures 4 and 5), the project managers of the Avionics and the Structures PDTs independently qualitatively predicted the effects of a systematic variation of goal incongruency on their own project teams. Project duration was anticipated to increase monotonically with goal incongruency in a relatively linear fashion. Project costs were predicted to have a "U" shape in which cost initially decreased as goal incongruency increased from zero to moderate levels and then began to increase as goal incongruency continued to higher levels. In regard to work process quality measures, the Avionics and Structures project managers could not intuitively predict the emergent effects.

Moreover, in the predictions of the Avionics PDT project manager, the effects of goal incongruency on the various performance indicators were more exaggerated than they were in the predictions of the Structures PDT project manager. In other words, the slopes of the curves that the Avionics project manager predicted for his own team were greater than those predicted by the Structures project manager for the Structure PDT.

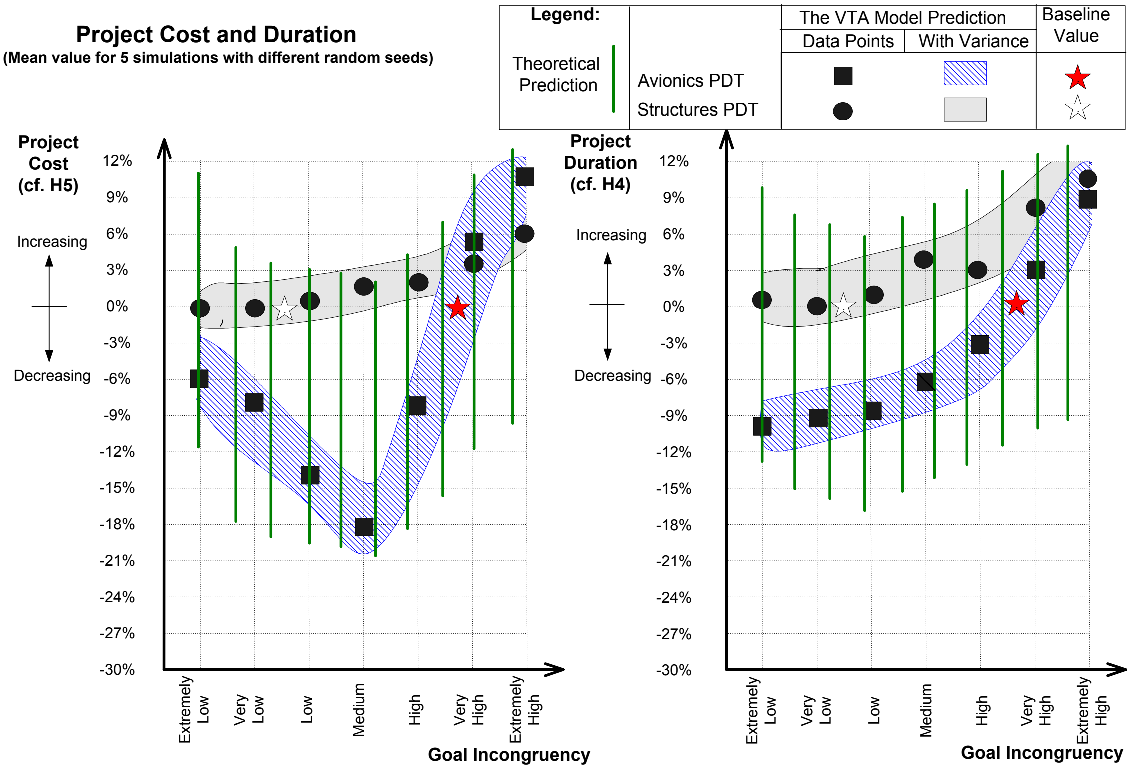

***Figure 4:* Simulated Work Process Cost and Duration vs. Goal Incongruency for Avionics and Structures.** Both graphs show goal incongruency on the horizontal axis. The left graph shows project cost on the vertical axis, and the right graph project duration. We used the initial Structures and Avionics models as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high. Simulation results agree qualitatively with organizational contingency theory. The results are statistically stable.

Cost was minimized at moderate to lower levels of goal incongruency both for Avionics and Structures in accordance with H5. Moreover, the fact that the graphs for the Avionics PDT are greater in amplitude and slope than the graphs for the Structures PDT indicates that the effect of goal incongruency on cost was greater for the Avionics PDT than for the Structures PDT, as hypothesized in H6. In the simulation, the intensified effect of goal incongruency in the Avionics PDT was due to the greater work process flexibility and interdependence between its members than present in the Structures PDT.

Duration was shortest at very low levels of goal incongruency and became progressively longer at higher levels of goal incongruency for Structures and Avionics—not as much U-shaped as H4 predicted, but the second derivative of the Structures and Avionics curves are clearly positive and we therefore conclude that results are consistent with H4. In addition, the fact that the graph for the Avionics PDT has more of a U-shape than the graph for the Structures PDT indicates that the effect of goal incongruency on duration was greater for the former PDT than for the latter, consistent with H6. Again, this intensified effect of goal incongruency can be attributed to the greater work process flexibility and interdependence in the Avionics PDT than in the Structures PDT.

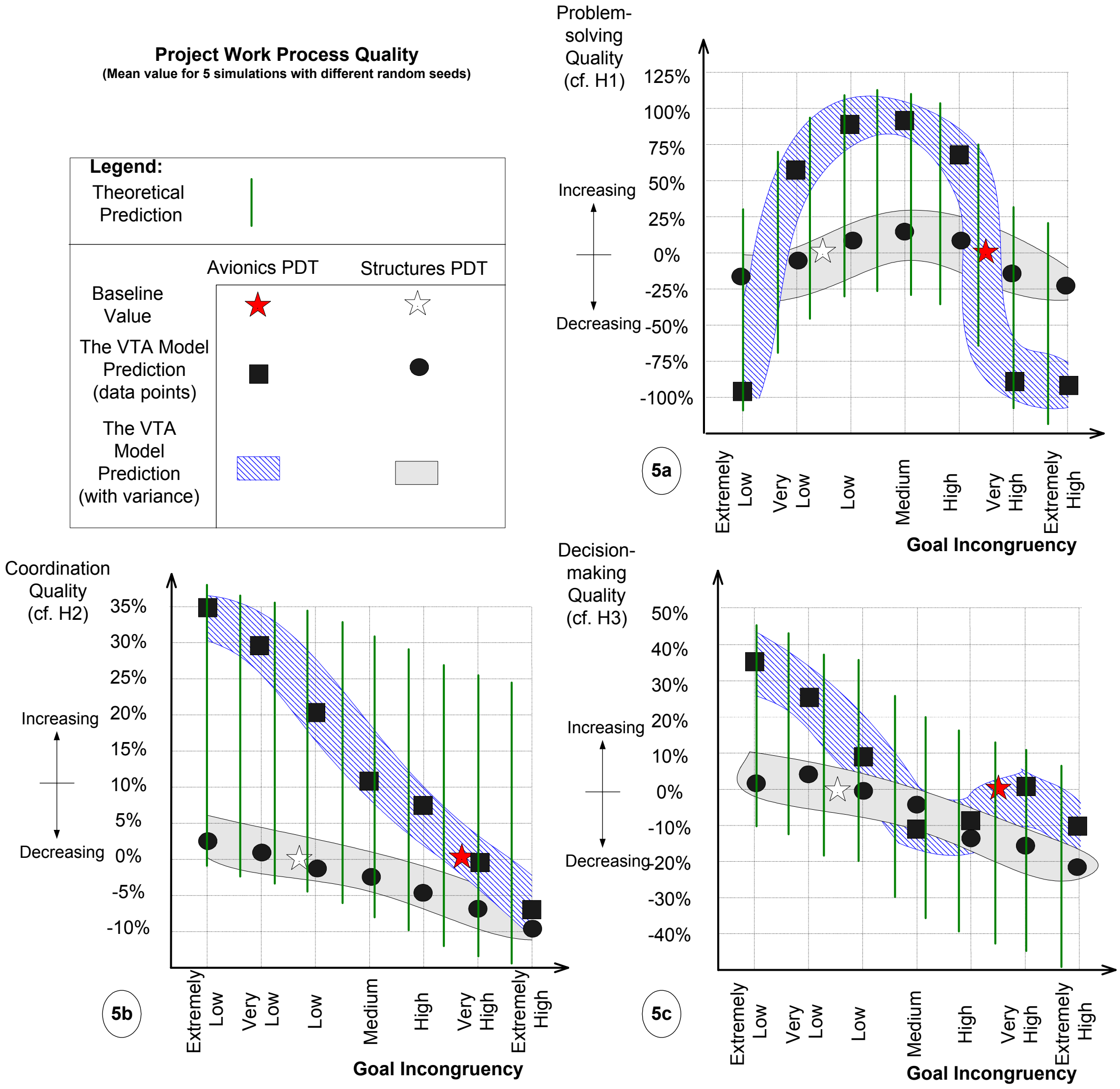

***Figure 5:* Simulated Work Process Quality for Avionics and Structures.** The three graphs above show the levels of goal incongruency on the horizontal axis. Graph, 5a at top right, shows problem-solving quality on the vertical axis; graph 5b, at the bottom left, coordination quality; and graph 5c, at the bottom right, decision-making quality. We defined problem-solving quality, coordination quality, and decision-making quality in section 5. We used the actual Structures and Avionics models as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high. Simulation results agree qualitatively with organizational contingency theory. The results are statistically stable.

The graphs for problem-solving quality for Avionics and Structures are, roughly, inverted U-shapes in which problem-solving quality is maximized at moderate levels of goal incongruency, as H1 predicts. At lower levels of goal incongruency, the productive non-conformances generated by searching for alternatives and goal clarifying outnumber the counterproductive non-conformances generated by steamrolling and politicking. However, at higher levels of goal incongruency, the latter two behaviors increase at a faster rate than the first two, until eventually more counterproductive non-conformances are generated. High levels of goal incongruency force actors to become overloaded by steamrolling and politicking communications. The increase in coordination volume forces actors to ignore exceptions as well as communications. The preponderance of missed exceptions and communications causes more exceptions to be generated later downstream, and, consequently, causes coordination and decision-making quality to decrease in agreement with H2 and H3. Again, the more pronounced effect of goal incongruency in the Avionics PDT than in the Structures can be attributed to the greater work process flexibility and interdependence of the Avionics PDT, as we expected from H6.

It is also clear that as goal incongruency increases, there is a distinct trade-off to be found between the five variables measuring project performance. Changing different parameters (e.g., goal incongruency) such that project performance will be maximized according to one indicator may negatively affect the other measures for project performance. Hence, before determining whether to promote or discourage goal incongruency within the team, a manager must first judge the relative importance of each performance indicator. Only then can our model of goal incongruency be applied to determine where on the performance curve the organization should be located and whether more or less goal incongruency is needed to achieve the desired performance. In providing a measure of the magnitudes of these trade-offs, our model suggests that the Avionics manager should nurture goal incongruency at a low-to-moderate level (he favored cost and duration above coordination and problem-solving quality). To change the level of goal incongruency, the Avionics manager could focus on selection of participants that were moderately goal congruent. Indeed, such an intervention would significantly reduce the Avionics backlog as well.

Because of a lack of sufficient prior experience with the modeling methodology, neither the investigators nor the project management intervened in the Avionics product development process based on our model predictions. The backlog and its impacts later materialized exactly when and where predicted, and had to be managed with a subsequent high impact on project cost and schedule. Moreover, during the demonstration launch, the launch vehicle veered off-course, and range control operators detonated the vehicle, along with its commercial payload. The subsequent analysis revealed two anomalies that caused loss of the demonstration launch vehicle:

- The first anomaly occurred 80 seconds after liftoff, when the vehicle suddenly pitched nose up. The pitch-up occurred because an electrical cable between the first-stage controller and the pitch actuator in the thrust vector control system experienced heating during flight in excess of its specifications.
- The second anomaly occurred 127 seconds after liftoff. The vehicle's inertial measurement unit (IMU), supplied by a subcontracting company, malfunctioned due to electrical arcing within the unit. The arcing was caused by exposing the high voltage circuits within the IMU to the low atmospheric pressure at high altitudes (LMMS Press Release, 1995).

The launch vehicle's instrumentation system provided extensive analog and digital data, enabling detailed analysis of the two anomalies. A company-led Failure Review Board was established to identify the cause of the loss of the vehicle and to recommend changes to eliminate the problems. The recommended changes to cables and flight-boxes were implemented, and the launch vehicle returned to flight successfully in 1997 (LMMS Press Release, 1997).

The VTA analysis predicted severe backlog problems in both the Cables and Flight-boxes subteams. The disastrous result of the first launch was caused by problems in the areas of responsibility of the Cables and Flight-boxes subteams. Our model results, therefore, provide ample evidence that product quality relates to process quality. The intuitive notion that the quality of an organization work processes affect ultimate product quality has also been demonstrated convincingly by several researchers in the facility engineering domain, most recently by Fergusson (1993). Hence models like VTA, which generate predictions of process quality, can provide indications of the levels of risk for product quality problems in particular subsystems.

7. Discussion

Since our long-range research goal is to provide project managers with a theory and tools to predict project behavior and performance through the development and analysis of a computational organizational model, it is extremely important that the model capture the key aspects of a project that determine project performance. The success of predicting emergent project behavior is fundamentally contingent on the accuracy and relevance of the rules of behavior that have been posited for the system at the micro-level. The assumptions regarding the nature of the constituent elements, as well as the rules that govern their interaction, determine the extent to which the emergent behavior generated by the simulation model will agree with both theory and real-world behavior. In order to ensure that our model captures the essentials of project behavior, extensive real-world validation is necessary.

The primary contribution of this paper is an innovative validation strategy. The validation strategy includes four validation methods:

- **Computational synthetic experiments:** We applied our model to a number of small synthetic test cases—"toy" organizations—simple enough models that their micro- and macro-behavior could be computed manually and compared to simulation predictions to test for internal representational validity (Thomsen *et al*., 1998b).
- **Retrospective validation and comparison with manager's "what-if" predictions:** We applied our model retrospectively to a completed real-world test case and then compared the simulated model predictions with the project outcome and the manager's "what-if" predictions to test for external representational validity.
- **Contemporaneous validation:** We applied our model to an on-going real-world test case and performed a series of experiments that produced forward predictions about the remaining project outcome to test for predictive validity.
- **Prospective validation with interventions:** In our final case study, we modeled the planned work process and organization for a real project and prospectively identified potential project performance problems. These were then used to guide management interventions. This successful intervention demonstrated the model's representational validity, predictive power, and its usability by managers.

We proposed this multi-stage validation strategy for emulation models and discussed how we applied it on the VTA model. The VTA model did not remain static during our three-year-long validation period, but was extended somewhat for each of the validation steps. We conducted two contemporaneous validation test cases of VTA. We performed a three-way comparison between the predictions of the underlying organization theory, the computational model outputs, and field data for these two case studies. We conducted the virtual experiments contemporaneously with project execution. For one of these test cases, VTA correctly predicted the risk of backlog in the external team developing an outsourced component of the avionics package, as well as a serious quality problem and resulting delays. In the other contemporaneous test case, no problems were predicted and none occurred. From this small set of test cases, we have gained some confidence that the VTA model can effectively describe fast-paced project plans and support organizations; it can also predict project schedule, process quality and cost risks. Further, from our prospective validation test case, we conclude that VTA can enable managers to identify, choose, carry out and manage interventions to reduce predicted risks.

We cannot necessarily attribute the Avionics case study project performance problems to the risk we pinpointed. The project might have had the same problems had the manager intervened in the engineering process; other exogenous factors might have contributed more significantly to the outcome than the factors represented in our model. However, since we modeled two radically different teams, the "exploitative" Structures team and the "explorative" Avionics team, and our model predicted outcomes consistent with the actual outcomes in both of these teams, we are encouraged about the generality and validity of our model.

Our two case study observations do not make up the usual statistical sampling approach according to which we can do large scale hypothesis testing and ANOVA testing. But there is a good deal to learn in this sequence of "sample of one" observations (March *et al.*, 1991). We have applied our model to a series of case studies (Thomsen *et al.*, 1998a, 1998c). VTA can be viewed as an organizational inference model when applied to a series of test cases. A series of test cases create a “web of inferences.” A web of inferences provides a framework and logic for learning from multiple samples of one.

Statistical evidence of predictive validity and efficacy of our model will come only from a series of intervention studies done concurrently with similar studies done without intervention. Nevertheless, our model has gained credibility, if not from statistical validity, then from the fact that it prospectively produced an outcome that was consistent with the end results of two different project teams that we observed.

In addition to performing more intervention studies using the VTA model, we also propose to do cross-model validation, i.e., "docking" (Axtell *et al*., 1996), between VTA and OrgCon (Burton and Obel, 1995). OrgCon is a heuristic implementation of macro-contingency theory. Both OrgCon and VTA are based on organizational contingency theory and an information-processing perspective of work, so they have essentially the same theoretical platform. It would, therefore, be theoretically sound as well as interesting to judge the degree to which the two models correspond in their recommended interventions for a particular organization. This form of cross-model validation on common data will help to advance the field of COS toward a true science.

8. Acknowledgments

We would like to express our appreciation to the Structures and Avionics teams in our collaborating aerospace company for their generous time and efforts in helping us to develop the computational models that we used as our case studies. We would also like to thank Yul J. Kwon for invaluable help during the data collection phase of our research.

9. References Cited

Argyris, C. (1970), *Intervention Theory and Method: A Behavioral Science View*. Reading, MA: Addision-Wesley Publishing Company.

Argyris, C. (1983), “Action Science and Intervention*,” The Journal of Applied Behavioral Science*, 19(2), 115-140.

Axtell, R., R. Axelrod, J. J. Epstein and M. D. Cohen (1996), "Aligning Simulation Models: A Case Study and Results," *Computational and Mathematical Organization Theory*, 1(2), 123-142.

Babbie, E. (1995), *The Practice of Social Research* (7th edition). Belmont, CA: Wadsworth Publishing Company.

Baligh, H. H., R. M Burton and B. Obel (1994), "Validating the Organizational Consultant on the Fly," in *Computational Organization Theory*, edited by K. M. Carley and M. J. Prietula, Hillsdale, NJ: Erlbaum Associates.

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

Carley, K. M. (1997), *Validating Computational Models*. Working Paper: Social and Decision Sciences, Carnegie Mellon University, Pittsburgh, PA.

Carley, K. M. and Z. Lin (1995), "Organizational "Designs Suited to High Performance Under Stress," *IEEE Transactions on Systems, Man, and Cybernetics, 25(1), 221-231.*

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.

Cohen, M. D., J. G. March and J. P. Olsen (1972), "A Garbage Can Model of Organizational Choice," *Administrative Science Quarterly*, 17(1), 1-25.

Cohen, P. R. (1995), *Empirical methods for artificial intelligence*. Cambridge, Mass.: MIT Press.

Eisenhardt, K. M. (1985), "Control: Organizational and Economic Approaches," *Management Science*, 2, 134-149.

Fergusson, K. J. (1993), *Impact of Integration on Industrial Facility Quality*. Ph.D. Dissertation, Department of Civil Engineering, Stanford University.

Galbraith, J. R. (1973), *Designing Complex Organizations*. Reading, MA: Addison-Wesley.

Galbraith, J. R. (1977), *Organization Design*. Reading, MA: Addison-Wesley.

Huberman, B. A. and T. Hogg (1995), "Communities of Practice: Performance and Evolution," *Computational and Mathematical Theory*, 1(1), 73-92.

Hyatt, A., N. Contractor, and P. M. Jones (1997), "Computational organizational network modeling: Strategies and an example*,"* *Computational and Mathematical Organizational Theory*, 2(4), 285-300.

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

Law, A. M. and D. Kelton (1991), *Simulation Modeling and Analysis* (2nd edition). New York, NY: McGraw-Hill.

LMMS (Lockheed Martin Missile and Space) Press Release, December 1995. "LMLV-1 Loss Linked To Two In-flight Anomalies."

LMMS (Lockheed Martin Missile and Space) Press Release, August 1997. "Lockheed Martin Launch Vehicle Successfully Launches NASA/TRW Lewis Satellite."

March, J. G. (1991), "Exploration and Exploitation in Organizational Learning," *Organization Science*, 2(1), 71-87.

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

March, J. G., L. S. Sproull and M. Tamuz (1991), "Learning From Samples of One or Fewer," Organizational Science, 2(1), 1-13.

Masuch, M. and P. LaPotin (1989), "Beyond Garbage Cans: An AI Model of Organizational Choice," *Administrative Science Quarterly*, 34(1), 38-67.

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).

Oralkan, G. A. (1996), *Explorer: A Computational Model of Organizational Learning in Response to Changes in Environment & Technology*. Ph.D. Dissertation, Department of Civil Engineering, Stanford University.

Ouchi, W. (1979), "A Conceptual Framework for the Design of Organization Control Mechanisms," *Management Science*, 25:833-848.

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

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

Thompson, J. D. (1967), *Organizations in Action: Social Science Bases in Administrative Theory.* New York: McGraw-Hill.

Thomsen, J. and Y. J. Kwon (1996), *Modeling the Lockheed Launch Vehicle Program*. DNV Research Report No. 96-2025, Oslo, Norway.

Thomsen, J., Y. J. Kwon, J. C. Kunz and R. E. Levitt (1996), "A Computational Approach to Modeling an Engineering Design Team," in *Proceedings of the Third Congress on Computing in Civil Engineering*, ASCE, Anaheim, CA, June 17-19.

Thomsen, J., M. A. Fischer and R. E. Levitt (1998a), *The Virtual Team Alliance (VTA):* An *Extended Theory of Coordination in Concurrent Product Development Projects*. CIFE Working Paper #44, Stanford University.

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

Tushman, M., and D. Nadler (1978), "Information Processing as an Integrating Concept in Organizational Design," *Academy of Management Review*, 3, 613-624.

Weick, K. E. (1979), *The Social Psychology of Organizing*. McGraw-Hill Inc.

Zeggelink, E. P. H., F. N. Stokman, G. G. Van de Bunt (1996), "The Emergence of Groups in the Evolution of Friendship Networks," *Journal of Mathematical Sociology*, 1(1-2), 29-55.

CHAPTER VI

Contributions and Suggested Future Work

Semi-routine, fast-paced projects with interdependent and concurrent activities and professional project participants from multiple organizations create unique management challenges. My dissertation focuses on the effects of goal incongruency between participants on project performance. The preceding four chapters (the "heart" of my dissertation) have presented my VTA model that extends the VDT information-processing framework with ideas from economic agency theory and social psychology to model behavior of goal-incongruent dyads. My VTA model allows project managers to balance organizational design and management policies in such a way that optimum performance is achieved for any given level of goal incongruency. Chapters II, III, IV, and V will be published as autonomous journal articles; they explicitly explain my claimed contributions to knowledge and my suggestions for future work. This chapter synthesizes the contributions of these papers, outlines a set of suggestions for future work, and concludes with some closing remarks.

1. Contributions to Knowledge

The central theme of my dissertation is to relax the limiting assumption in an organizational design perspective that treats actors as "engineering nerds" with fully congruent goals. I argue that product developers should rather be modeled as professional teleological actors with potentially incongruent goals. By adopting the abstractions employed in the information-processing view of organizations, my VTA model avoids the complexity of decision-theoretic or utility-based representations of problems and allows me to focus on the effects that different work processes and organizational designs have on communication and coordination in project organizations. I show that a simple information-processing model of goal incongruency can provide powerful and useful predictions about project performance.

To provide a summary of my contributions to knowledge, this chapter extracts and integrates the contributions of chapter II, III, IV, and V to computational organizational theory and the body of social science knowledge, and explains their contributions to engineering management theory and practice.

1.1 Contributions to Computational Organizational Theory

Computational organizational theory has provided the scientific community with several lucid models that have provided valuable insights into organizational phenomena (e.g., Carley *et al.*, 1992; Cohen *et al.*, 1972; Huberman and Hogg, 1995; Jin and Levitt, 1993; Oralkan, 1996; Masuch and LaPotin; 1989). However, the implications of these findings for practice have been limited because the models have been intentionally simple and abstract, and used primarily for generating new theory fragments.

The Virtual Design Team (VDT) (Cohen, 1992; Christiansen, 1993; Jin and Levitt, 1996) showed that computational organizational models could provide accurate predictions for *routine, fast-paced* projects in which all participants were assumed to have *congruent* goals. My contributions to computational organizational theory consist of my extensions of the existing VDT information-processing model to incorporate characteristics of *semi-routine, fast-paced* projects as well as the notion that project participants could have *incongruent goals*. I have tried to strike a balance between maintaining a rich representation, but keeping it parsimonious enough to maintain theoretical transparency and modeling feasibility.

My Virtual Team Alliances (VTA) framework introduces a simplified representation of actor perspectives and priorities to support simulation, in contrast to decision-theoretic approaches that focus on gathering information about all alternatives for each decision (Howard and Matheson, 1983). In my information-processing approach, I do not need to specify the characteristics of each alternative an actor considers in making a decision among alternatives. Rather, I simply have to estimate the flexibility of a particular activity and assume that each of the actors, based on its goal priorities, will select a solution that is intended to meet the activity requirements (Figure 1). This abstraction avoids the complexity of decision-theoretic or utility-based representations of problems and allows us to focus on the effect that different process and organizational designs have on communication and coordination in project organizations.

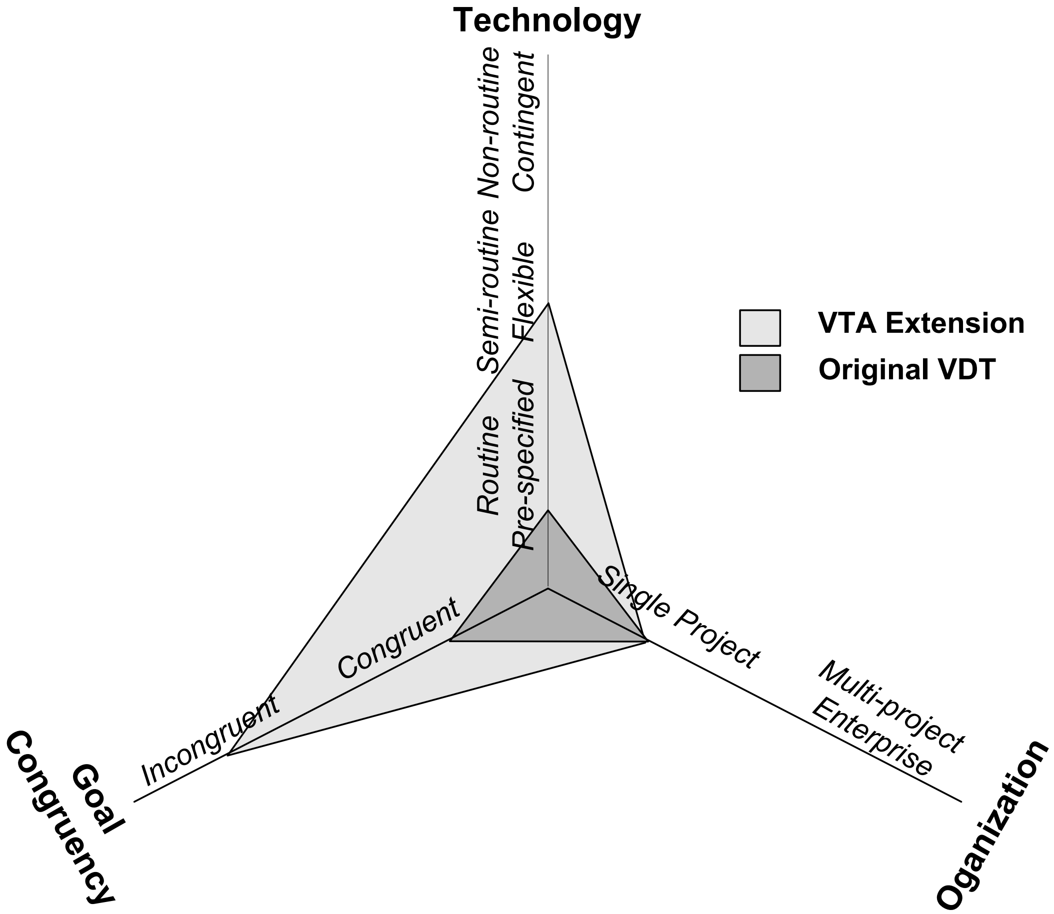

Figure 1: **The VTA Organization Design Space.** VTA builds off VDT to represent product development organizations in industries such as automobile and aerospace, in which much of the work is outsourced to external component suppliers whose goals may be more or less congruent with those of the prime contractor.

In my VTA model, I describe a total of seven "canonical" interaction processes in response to goal incongruency: three for vertical relationships, and four for lateral relationships. The responses are not necessarily mutually exclusive. The extent to which each is invoked is contingent on the level of goal incongruency as well as other organizational factors.

1.1.1 Goal Incongruency Behaviors between Supervisors and Subordinates

Goal incongruency in supervisor-subordinate relationships will directly affect the managerial behavior of the supervisor. Therefore, economic agency theory researchers are concerned about the optimal structuring of control relationship and incentive schemes in the presence of goal incongruency between supervisors and subordinates (Eisenhardt, 1989). My model depicts actors as altruistic information-processing units in contrast to the assumption of economic agency theory about self-interested, incentivized actors. In my information-processing model, goal incongruency will cause the supervisor to change the frequency with which it monitors the subordinate and the amount of decision-making authority it confers on the subordinate. Hierarchical communication requires time on the part of the supervisors and subordinates in that communication items must be initiated, attended to, and responded to. However, hierarchical communications generally lead to an increase in decision-making quality, since more exceptions are detected and handled properly. This increase, on the other hand, may be offset by a decrease in coordination quality if the hierarchy becomes overloaded with communications.

It is clear that there will be some optimal level of hierarchical communication—too little may result in an excess of exceptions as a consequence of goal incongruency and too much may overload actors to the point that they become seriously backlogged. Amount of hierarchical communication is especially a concern for supervisors with many subordinates—i.e., those with a large span of control. An optimal distribution of decision-making authority for a single vertical chain of command will minimize bottlenecks that arise due to overloaded information-processing nodes. A highly centralized vertical chain will cause exceptions to be referred to higher levels of management. If the number of exceptions that any one actor must process is very great, it may become overloaded. Overload increases the number of non-attended exceptions and, ultimately, decreases decision-making quality. Hence, an ideal distribution of authority will prevent too many exceptions from being directed toward any one actor.

Determining this optimal distribution is non-trivial. It cannot easily be determined without simulation. It is not the case, for example, that a high level of centralization of decision-making will necessarily result in superior decision-making quality. Higher level managers may exhibit a preference for reworking all exceptions. A manager who is overloaded with exceptions may not attend to other exceptions in a timely manner. Exceptions that are not attended to will be ignored by default, leading to a decrease in decision-making quality. Therefore, determining the optimal distribution of authority depends on the number of exceptions that are generated and detected in each vertical chain and to whom they are sent for a decision.

1.1.2 Goal Incongruency Behaviors between Peers

A comprehensive model of organizational behavior needs to consider the lateral interaction between project members as well as the interactions between managers and subordinates. The sheer complexity of modern engineering artifacts causes work in project teams to be more integrated and interdependent (Simon, 1996). Drawing on March and Simon (1993, pp. 149-152), I modeled four responses that interdependent peer actors choose in reacting to goal incongruency: steamrolling, politicking, searching for alternatives, and clarification of goals.

VDT is based on the premise that coordination work takes time. It delays project completion, increases costs, and affects work process quality. For an engineering task in which coordination is crucial, observation suggests that, even though actors easily tend to become overloaded with communications, they may also generate better solutions in terms of cost and duration as a result of coordination. Extending the VDT peer-to-peer “FYI” type of communication to include "steamrolling," "politicking," "searching for alternatives," and "clarification of goals" types of communication adds new kinds of predictive power. For example, my computational experiments indicated that neither extreme of goal incongruency would be conducive to maximizing project cost. Moreover, my results suggest that the optimal level of goal incongruency is influenced by organizational differences (work process flexibility, interdependence strength between activities, team experience, etc.) between the projects. Figure 2 gives a qualitative a comparison between VTA and other computational modeling frameworks.

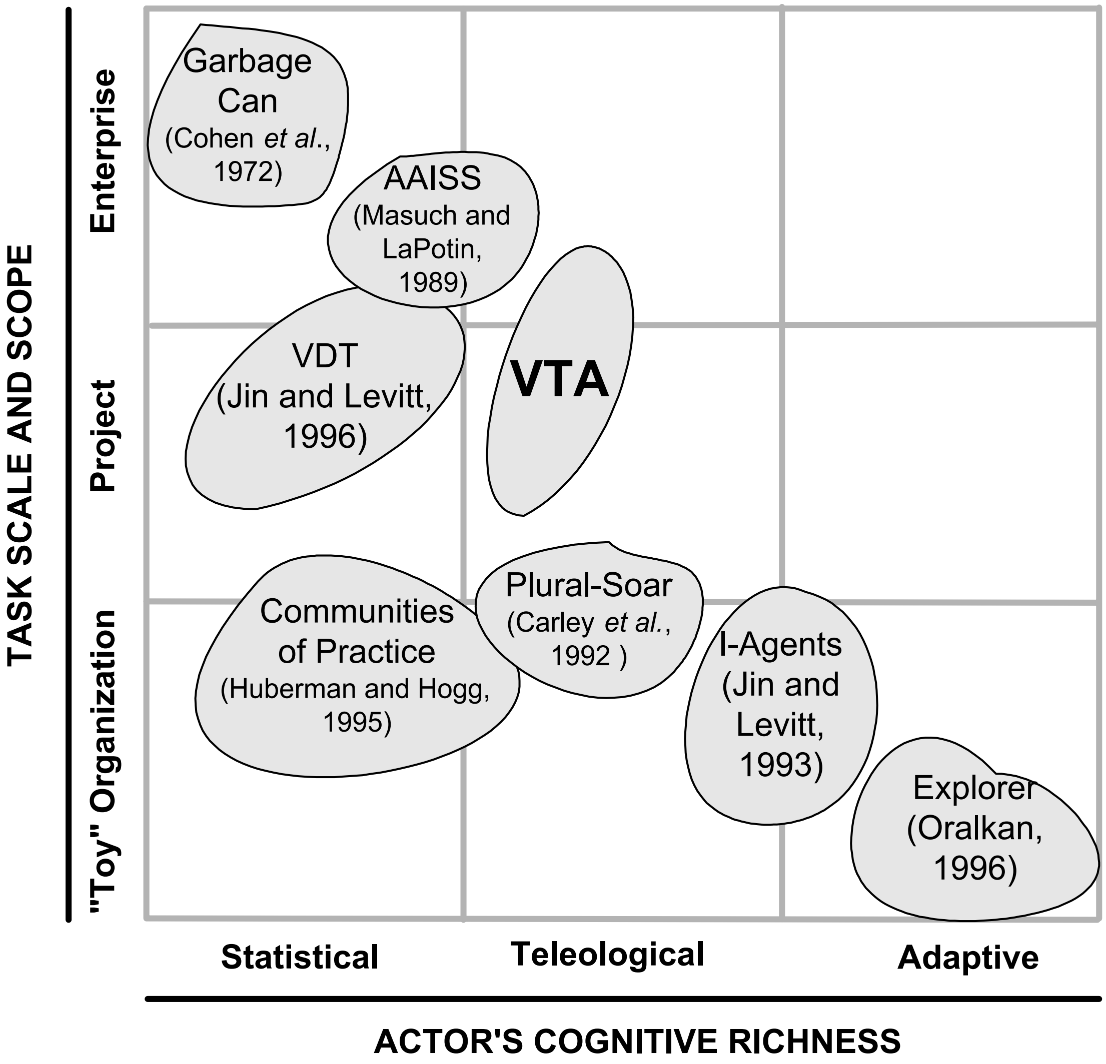

Figure 2: **The VDT Framework and my newer VTA Framework in relation to other Computational Modeling Frameworks, based on the Task Scale and Scope and the Actor's Cognitive Richness.** "Toy" organizations are simple, hypothetical organizations, which have been developed to test theory. Models applied to real-world organizations such as project organizations and enterprises capture some aspects of real organizations. Thus, results of the models can be validated against the real world. Practical multi-actor systems may be characterized by the degree of cognitive richness of their actors. We distinguish between statistical, teleological, and adaptive actors. A statistical actor reacts to changes in the environment (e.g., activity complexity) or to messages from other actors. It is not able to reason about its goals. Teleological actors act and interact according to their goals. An adaptive actor acts and interacts according to its goals and has the ability to revise its goals based on the results of its previous actions.

1.1.3 Validation Approach

Validation of complex simulation models, with multiple inputs and feedback loops, is a challenging problem that has received considerable attention in the literature (Burton and Obel, 1995). Another of my contributions to computational organizational theory lies in my innovative validation approach. I used four kinds of validation:

- **Computational synthetic experiments:** I applied my model to a number of small synthetic test cases—"toy" organizations—simple enough models that their micro- and macro-behavior could be computed manually and compared to simulation predictions to test for internal representational validity.
- **Retrospective validation and comparison with manager's "what-if" predictions:** I applied my model retrospectively to a completed real-world test case and then compared the simulated model predictions with the project outcome and the manager's "what-if" predictions to test for external representational validity.
- **Contemporaneous validation:** I applied my model to an on-going real-world test case and performed a series of experiments that produced forward predictions about the remaining project outcome to test for predictive validity.
- **Prospective validation with interventions:** In my final case study, I modeled the planned work process and organization for a real project, and prospectively identified potential project performance problems. These were then used to guide management interventions. This demonstrated the model's representational validity and its usability by managers.

1.2 Contributions to Social Science

A main criticism of contingency theory is that most of the concepts used in the theory are too aggregate in their predictions, and thus disconnected from decision variables actually controlled in organization design (Argyris, 1972; Pfeffer, 1997; Starbuck, 1981). For instance, formalization and centralization are seldom directly changed but result from a series of more specific changes, e.g., in the authority of particular managers, or the frequency of formal meetings. VTA extends existing contingency theory (Thompson, 1967) and Galbraith's information-processing theory (Galbraith, 1973, 1977) and focuses attention on real-world organizational design decision variables that managers can manipulate directly.

Galbraith and other contingency theorists focus on organizational behavior at the level of the entire organization and do not concern themselves with the internal dynamics of the organization. I have extended contingency theory to develop a micro-contingency model of goal incongruency and organizational behavior. My micro-contingency theory provides predictions and supports interventions that are directly related to managerial design variables. My model uses actors and the relationships between pairs of actors as the fundamental units of analysis. I implemented this model in the VTA simulation framework to help researchers and practitioners design their work processes and organizations in the same way engineers now design bridges, airplanes and semiconductors—by synthesizing, analyzing and evaluating alternative "virtual prototypes" of their organizations. I have demonstrated that the VTA micro-contingency theory makes predictions that are both theoretically and practically interesting.

1.3 Contributions to Engineering Management

My contribution to engineering management and practice is an explicit methodology for deriving key attributes of work processes (activity flexibility, complexity, uncertainty, and interdependence strength) and actors (goal incongruency) in semi-routine, fast-paced projects within the framework of organizational contingency theory. My representational framework can 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, I have shown that my methodology provides most value if it is combined with computational organizational simulation using my VTA simulation. Specifically, I introduced mechanisms of goal incongruency into my VTA model, collected data from two aerospace projects and one subsea satellite development project regarding participant goals, and compared observations with simulated predictions. I learned that my goal incongruency model usefully predicts important effects on project performance caused by changing levels of goal incongruency between project participants.

By using the VTA dynamic simulation framework, I was able not only to provide the cooperating project managers with measurable output predictions (participant backlogs, project cost, duration, and work process quality) but also to predict factors or processes that contribute to potential performance problems. I prospectively presented my model and results to one of my cooperating project managers. The results predicted potential future bottlenecks in the work process and suggested that performance would be significantly affected by changes in goal incongruency between project participants. The manager considered my results, discussed possible corrective actions, and decided to make interventions to facilitate smooth and timely coordination between project participants. This intervention study provides direct evidence, in the form of an empirical proof, that my model can be useful in practice (Argyris, 1970; 1983).

Providing a computational model and a method that give advice in regard to managerial organizational challenges, predict potential project risks and, subsequently, forecast *a priori* the effects of different feasible interventions, goes beyond the scope and precision of traditional project management tools such as Critical Path Models (figure 3). A manager who uses my computational organizational model can conduct “what-if” experiments that represent and differentiate between different feasible intervention strategies and decide on an intervention that provides the best trade-off in regard to cost, duration, and work process quality.

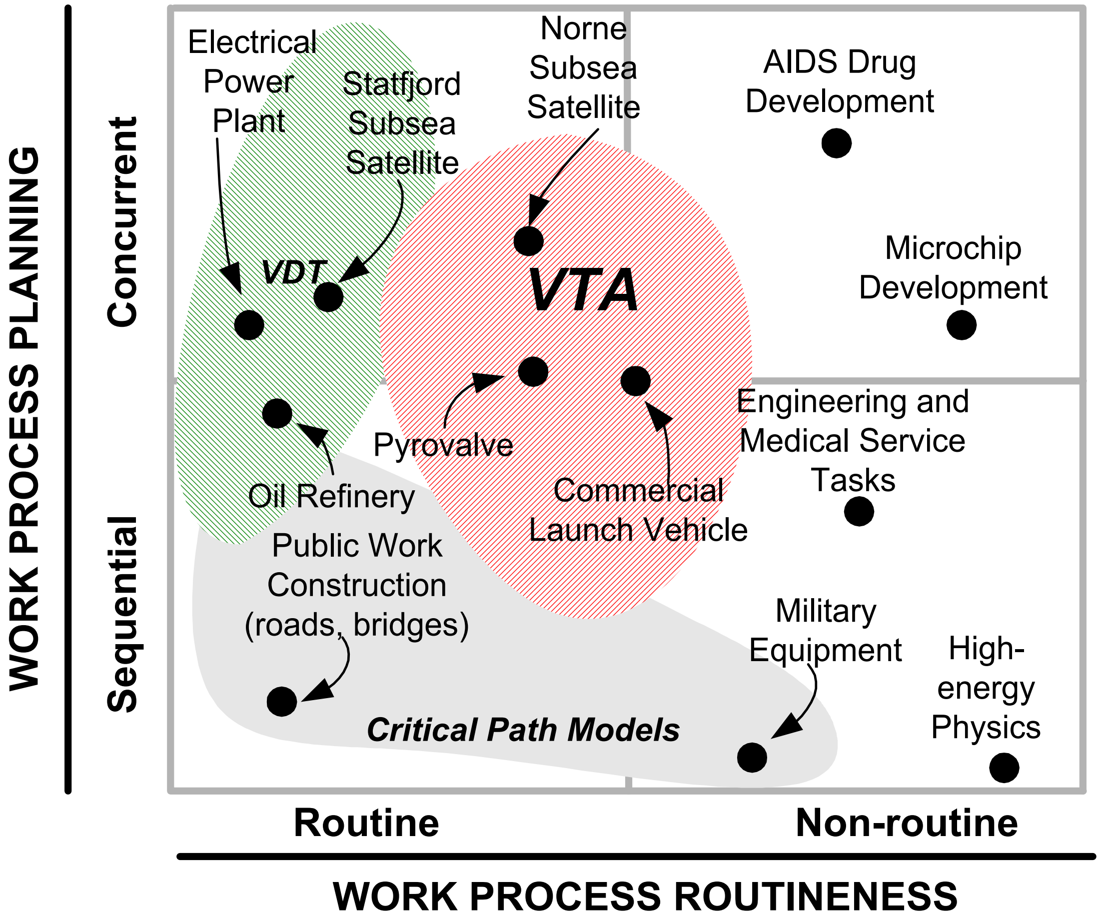

Figure 3: **Range of Applicability of Critical Path Models, VDT, and the VTA Model**. The figure compares the areas of applicability of different models (bubbles) according to two dimensions: "work process planning" (sequential vs. concurrent) and "work process routineness" (routine vs. non-routine). VTA can be applied to semi-routine, fast paced projects, VDT to routine, fast-paced projects such as power plant development, Critical Path Models to sequential projects such as public construction work, but also to fairly non-routine processes such as the development of new military equipment using a stochastic scenario analysis approach. Critical Path Models, VDT and VTA are not applicable to contingent work processes, such as those often found in engineering maintenance and medical service tasks. Long-term basic research, such as high-energy physics research, is located to the far right side of the figure. The AIDS drug development is the same kind of basic exploration, but the AIDS drug development projects are much more fast paced because of social needs. None of these endeavors is suitable for analysis in Critical Path Models, VDT or VTA models.

1.4 Contributions to Total Quality Management

My contribution to TQM is my development of a conceptual framework and a computational organizational model for analyzing the quality performance of an organization that relies on the prominent information-processing view of organizations (Pfeffer, 1996, p. 70). Advocates of the TQM approach assume that TQM methods are *holistically* and *universally* beneficial for all organizations (Crosby, 1979; Deming, 1982;

Juran, 1992). Based on Sitkin, *et al*., (1994), my *micro-contingency* approach to total quality management and organizational design rejects this assumption considers the specific characteristics of the work process of an organization, hierarchy, personnel makeup, and environment before prescribing methods to improve quality. VTA moves the focus of quality management from measuring and controlling the quality of work processes to the next level—measuring and controlling the quality of the organizations that execute work processes.

Within the TQM framework (Druckman *et al*., 1997), the definition of quality is neither precise nor consensual. My model, however, measures and controls the quality of the organizations that design and execute work processes through the metrics of an actor backlogs, problem-solving quality, coordination quality, and decision-making quality as well as project cost and duration. Improvement in one organizational performance dimension usually comes at the expense of degradation in performance of another. Modeling an organization formally in my framework allows project managers to increase their understanding of project dynamics through both process formalization and analysis of results. My metrics provides quantitative measures to support these managerial trade-off decisions in a rigorous and repeatable manner. VTA is uniquely able to predict the impact of managerial interventions on both project efficiency and work process quality.

There have been several fruitful applications of organizational science concepts to the quality management process. For example, quality management practices have been related to issues such as strategic management (Powell, 1995). I claim that my research represents a novel and unique initiative to apply theories and methods within the field of Computational and Mathematical Organizational Theory to extend the applicability of Total Quality Management (TQM) for project-oriented work.

2. Suggested Future Work

Since my long-range research goal is to provide project managers with a theory and tools to predict project behavior and performance through the development and analysis of a simulation model, it is extremely important that the simulation model capture the key aspects of a project that determine project performance. The success of VTA in predicting emergent project behavior is fundamentally contingent on the accuracy and relevance of the micro-level rules of the system. The assumptions regarding the nature of the constituent elements, as well as the rules that govern their interaction, determine the extent to which the emergent behavior generated by the simulation model will agree with both theory and real-world behavior.

Three directions need future exploration. First, in order to ensure that my model captures the essentials of project behavior, more real world, as well as cross-model validation is necessary. Second, many engineering tasks are by the nature contingent, and my computational model should become rich enough to capture the contingent aspects of work. Third, real-world project participants adapt their goals during the course of a project. A very challenging task is to include the notion of learning in an information-processing model of organizational behavior. These are not the only explorations that I could suggest, but they are those I think most important.

2.1 Statistical Validity and Cross-model Validation

My three case study observations do not make up the usual statistical sampling approach on which I can do the usual hypothesis testing and ANOVA testing. The question is, can I still learn and generalize from three single case studies? A flippant answer is that I did learn significantly more than if I had studied no projects. The more complete answer is that there is a good deal to learn in this sequence of "sample of one" observations (March *et al.*, 1991). The belief that we must have huge samples to learn about human behavior and organizational performance is not necessarily valid. Human nature is not that variable in organizational settings. Simon suggests about a dozen observations to get a fairly good understanding for the range of behavior one is likely to encounter in project teams (Simon, 1997, p. 399).

Statistical evidence of the predictive validity and efficacy of my model will come only from a series of successful intervention studies done in contrast with similar studies done without intervention. Nevertheless, my model has gained credibility if not from statistical validity, then from the fact that the project manager found it valuable in performing an intervention. My model prospectively produced predictions consistent with the results of the manager’s intervention.

In addition to performing more intervention studies using the VTA model, I also propose to do cross-model validation, i.e., "docking" (Axtell *et al*., 1996), between VTA and another model, OrgCon (Burton and Obel, 1995). OrgCon is a heuristic implementation of macro-contingency theory. Both OrgCon and VTA are based on organizational contingency theory and an information-processing perspective of work. They have essentially the same theoretical platform. It would therefore be theoretically sound as well as interesting to judge the degree to which the two models correspond in their recommended interventions for a particular organization.

2.2 Contingent Work Processes

My model is not applicable to contingent work processes, such as those often found in engineering maintenance and medical service tasks. 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 within a particular setting, I would have to develop an enriched set of micro-behavior to model the conditional aspects of these tasks, and determine new product and process quality evaluation metrics.

2.3 Adaptation by Project Participants

Procurement presents a classical goal dilemma: an engineer may want to hold on to a design to improve its quality, but schedule pressures encourage releasing the design to procurement as early as possible. In the traditional aerospace industry procurement model, manufacturing could accommodate design changes relatively easily when design and manufacturing were done by the same organization. With manufacturing by outside contractors, engineering change orders often become more formal, expensive and time-consuming. The agile organization forces greater tension regarding time-quality trade-offs. I can represent such tensions through goal incongruency between project participants. However, in my model, goal incongruency is static. That is, there is no change in goal incongruencies over the course of the project. Such a view of goal incongruency, however, is at odds with actual behavior, since people adopt different goals over time. For example, engineering professionals customarily prefer to attend to activities "on the critical path," and the critical path can change several times during a project. A more detailed model of goal incongruency would account for learning and adaptation by individuals and view goal incongruencies as dynamic variables. I would need to add dynamic goal modification methods to the simulator that allows actors to adjust their goals during a simulation based on factors such as status on the critical path and different estimates of activity risk.

3. Closing Remarks

In my research proposal “Modeling the Effects of Goal Incongruency on Project Team Performance,” (Thomsen, 1995), I asked the following research questions: (1) *As the level of goal incongruency among actors varies, how does it moderate the effect of organizational variables on emergent project performance? (2) What are the behavioral mechanisms that produce these emergent project performance effects?* I specified a set of resultant research activities to answer these questions. Having carried out the research activities I ended up with four papers and a corresponding set of claimed contributions. The appropriate question to ask is whether my contributions provide answers to my research questions.

My claim, as laid out in considerable detail in the four papers, is that my work satisfactorily answers both my research questions. My Virtual Team Alliance (VTA) representation of semi-routine, fast-paced project organizations consisting of professional teleological actors with potentially incongruent goals is formal and executable so that a practitioner can run a set of exploratory simulations that are consistent, methodologically reproducible, and based on well-founded organization theory principles. My model constitutes a testable information-processing theory of the effects of goal incongruency in semi-routine, fast-paced project organizations. I retrospectively validated my model on an offshore field development project, contemporaneously on two portions of an ongoing aerospace launch vehicle project, and prospectively on a project aimed at developing a new generation of pyrovalves for positioning satellites in space.

My VTA model provides a modern approach to "project enterprise engineering." By running suites of simulations to analyze the effect of different model input variables (e.g., activity flexibility, interdependence strength, project participants), VTA can provide managers with predicted outcomes prior to actual implementation. This testing of "virtual prototypes" of real enterprises, I claim, represents my contribution in moving computational organizational modeling in the direction of true "organizational engineering."

CHAPTER VII

Bibliography[15]

Amason, A. (1996), "Distinguishing the effects of functional and dysfunctional conflict on strategic decision making: Resolving a paradox for top management teams," *Academy of Management Journal*, 39, 123-148.

Argyris, C. (1970), *Intervention Theory and Method: A Behavioral Science View*. Reading, MA: Addision-Wesley Publishing Company.

Argyris, C. (1972), *The applicability of organizational sociology*. London: Cambridge University Press.

Argyris, C. (1983), "Action Science and Intervention*," The Journal of Applied Behavioral Science*, 19(2), 115-140.

Axtell, R., R. Axelrod, J. J. Epstein and M. D. Cohen (1996), "Aligning Simulation Models: A Case Study and Results*," Computational and Mathematical Organization Theory*, 1(2), 123-142.

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

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

Carley, K., J. Kjaer-Hansen, A. Newell, M. Prietula (1992), "Plural-Soar: A Prolegomenon to Artificial Agents and Organizational Behavior," in M. Masuch and M Warglien (Eds.), *Artificial Intelligence in Organization and Management Theory*, Amsterdam: North-Holland, 87-118.

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

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.

Cohen, M. D., J. G. March and J. P. Olsen (1972). "A Garbage Can Model of Organizational Choice," *Administrative Science Quarterly*, 17(1), 1-25.

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[15] This bibliography contains the references that I have cited in Chapters I and VI.

Crosby, P. B. (1979), *Quality is Free*. New York: McGraw-Hill.

Deming, W. E. (1982), *Ouality, Productivity, and Competitive Position*. Cambridge, MA: MIT Center for Advanced Engineering Study.

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

Druckman, D., J. E. Singer and H. V. Cott (Eds.) (1997), *Enhancing Organizational Performance*. Washington DC: National Academy Press.

Eisenhardt, K. M. (1985), "Control: Organizational and Economic Approaches," *Management Science*, 2, 134-149.

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

Galbraith, J. R. (1973), *Designing Complex Organizations*. Reading, MA: Addison-Wesley.

Galbraith, J. R. (1977), *Organization Design*. Reading, MA: Addison-Wesley.

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.

Huberman, B. A. and T. Hogg (1995), "Communities of Practice: Performance and Evolution," *Computational and Mathematical Theory*, 1(1), 73-92.

Jehn, K. (1995), "A multimethod examination of the benefits and detriments of intragroup conflict," *American Journal of Sociology*, 82, 929-964.

Jin, Y. and R. E. Levitt (1993), "I-Agents: Modeling Organizational Problem Solving in Multi-Agent Teams," *Intelligent Systems in Accounting, Finance and Management*, 2, 247-270.

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

Juran, J. M. (1992), *Juran on Quality by Design*. New York: Free Press.

Levinthal, D. (1988), "A Survey of Agency Models of Organizations," *Journal of Economic Behavior and Organization*, 9, 153-185.

Masuch, M. and P. LaPotin (1989), "Beyond Garbage Cans: An AI Model of Organizational Choice," *Administrative Science Quarterly*, 34(1), 38-67.

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

March, J. G., L. S. Sproull and M. Tamuz (1991), "Learning From Samples of One or Fewer," *Organizational Science*, 2(1), 1-13.

Milgrom, P and J. Roberts (1992), *Economics, Organization & Management*. Prentice-Hall Inc.

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

Oralkan, G. A. (1996), *Explorer: A Computational Model of Organizational Learning in Response to Changes in Environment & Technology*. Ph.D. Dissertation, Department of Civil Engineering, Stanford University.

Ouchi, W. (1979), "A Conceptual Framework for the Design of Organization Control Mechanisms," *Management Science*, 25, 833-848.

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

Pelled, L. (1996), "Demographic diversity, conflict, and work group outcomes: An intervening process theory," *Organization Science*, 7, 615-631.

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

Pfeffer, J. (1997), *New Directions for Organizational Theory*. New York, NY: Oxford University Press.

Powell, T. C. (1995), "Total Quality management as competitive advantage: A review and empirical study," *Strategic Management Journal*, 16, 15-37.

Simon, H. A. (1996), *The Sciences of the Artificial* (3rd edition). Cambridge, MA: MIT Press.

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

Sitkin, S. B., K. M. Sutcliff and R. G. Schroeder (1994), "Distinguishing Control From Learning in Total Quality Management: A Contingency perspective," *Academy of Management Review*, 19, 537-564.

Starbuck, W. H. (1981), "A trip to view the elephants and the rattlesnakes in the garden of Aston," in A. H. Van de Ven and W. J. Joyce (Eds.), *Perspectives on organization design and behavior*, 167-198, New York, NY: Wiley.

Thompson, J. D. (1967), *Organizations in Action: Social Science Bases in 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. (1995), *Modeling the Effects of Goal Incongruency on Project Team Performance*. Unpublished Ph.D. proposal manuscript, Stanford University, Department of Civil and Environmental Engineering.

Watson, W., K. Kumar and L. Michaelson (1993), "Cultural diversity's impact on interaction process and performance: Comparing homogeneous and diverse task groups," *Academy of Management Journal*, 36, 590-602.

Weick, K. E. (1979), *The Social Psychology of Organizing*. McGraw-Hill Inc.

Williamson, O. E. (1979), "Transaction-cost economics: The governance of contractual relations," *Journal of Law and Economics*, 22, 3-16.