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By

Jan Thomsen, John C. Kunz, and Raymond E. Levitt

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

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

Designing Quality into Project Organizations through Computational Organizational Simulation[1]

JAN THOMSEN, JOHN C. KUNZ, and RAYMOND E. LEVITT
Center for Integrated Facility Engineering,
Stanford University School of Engineering, CA 94305-4020

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.

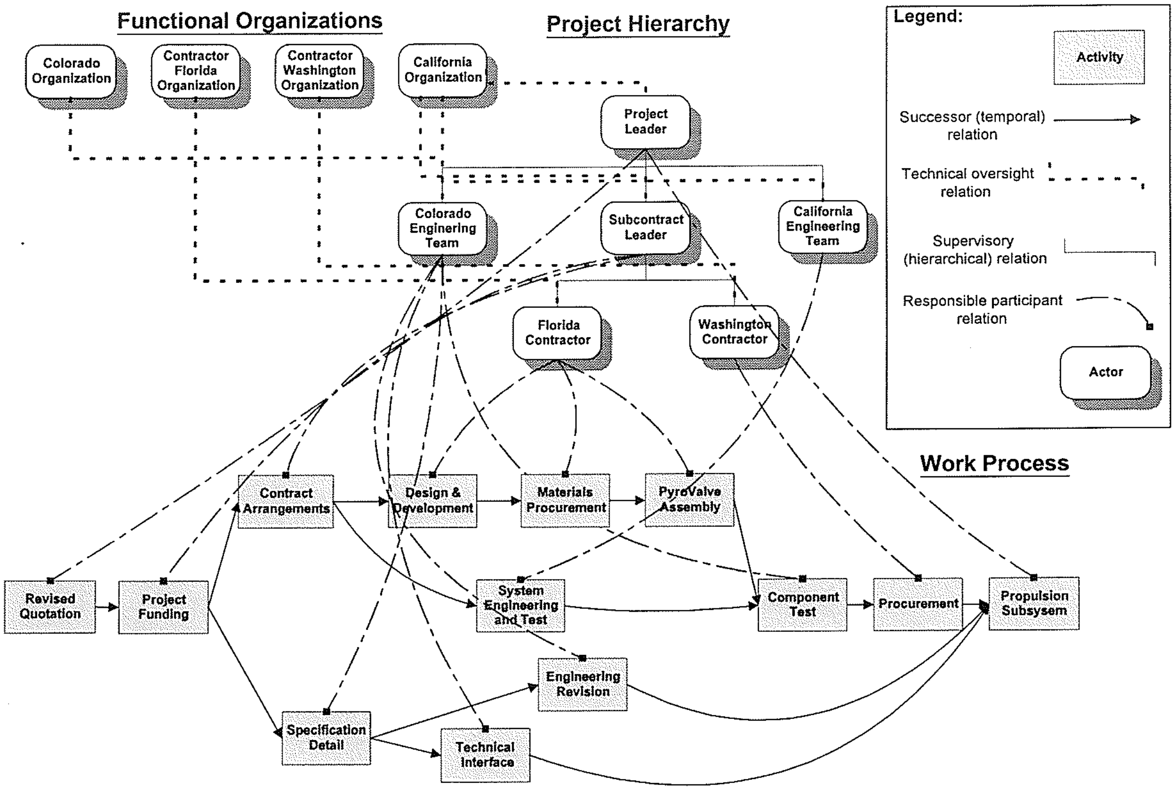

Figure 1: **The Pyrovalve Development Project Work Process and Organizational Hierarchy**. In our conceptual model, a project includes participants (embedded in a hierarchical organizational structure) and the activities (the Critical Path (CPM) model), which are interrelated. That is, each project participant 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*[2]*? 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 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

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[2] 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.

> 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.

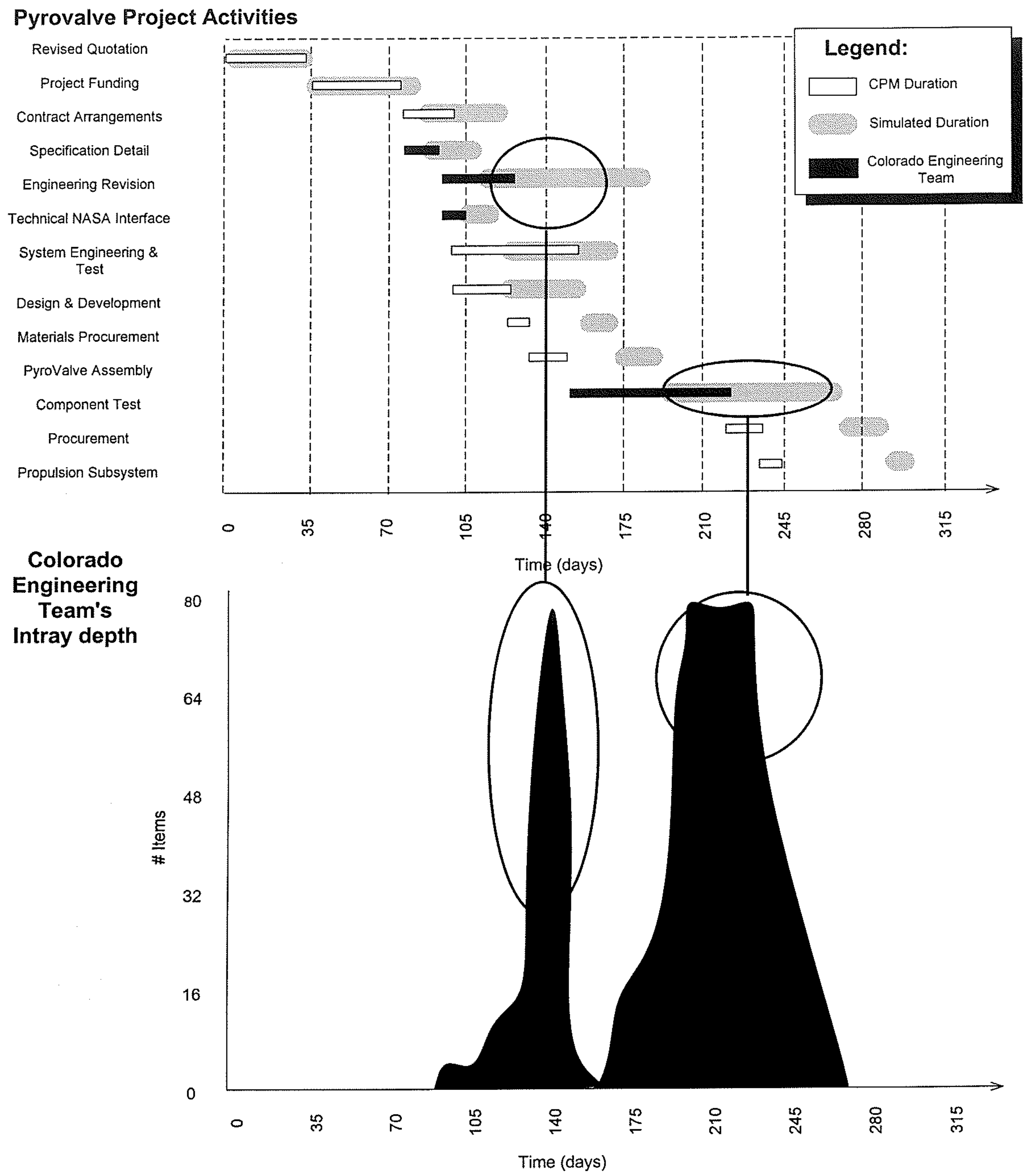

Figure 2: **Bottlenecks and Overloads in the Case Study Model.** The top diagram is a Gantt chart of the VTA simulation. The black or white bars represent durations for each activity anticipated by the CPM. The thicker gray bar around each black or white bar represents the predicted duration of that 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.

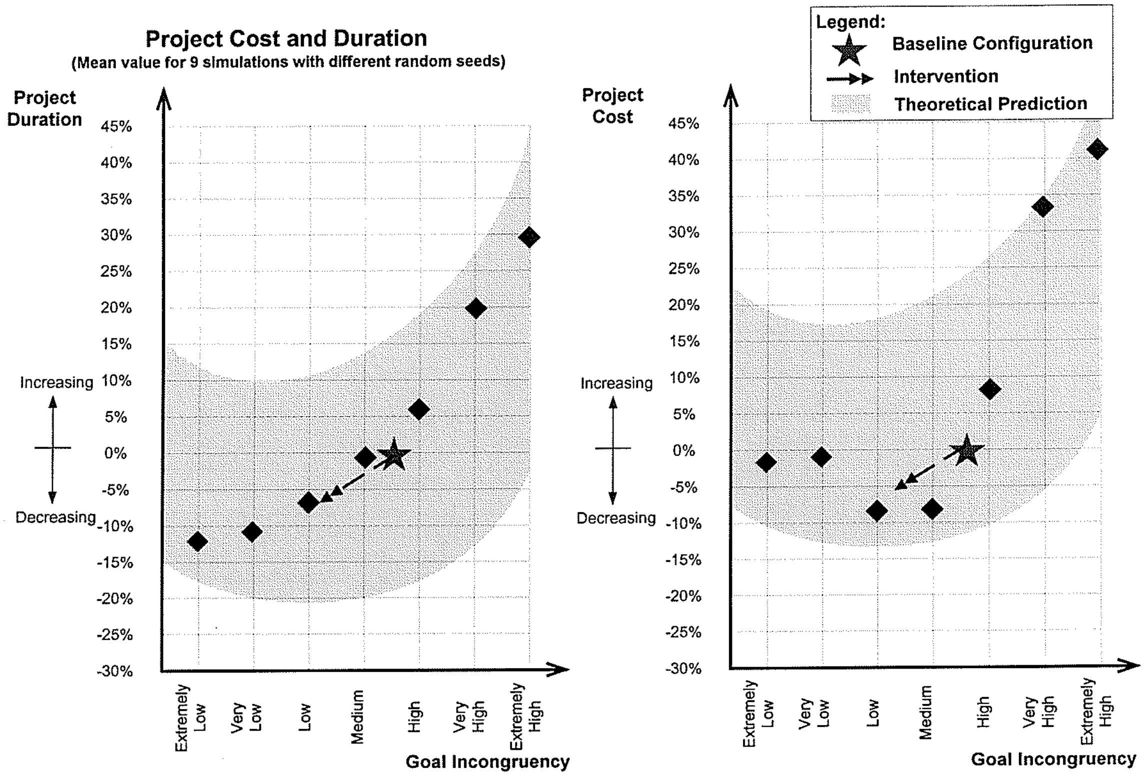

Figure 3: **Simulated Work Process Efficiency vs. Goal Incongruency**. The graphs show goal incongruency on the horizontal axes and change in project duration and cost on the vertical axes. We used the initial input model as a baseline reference-point and changed all actor-actor goal matches to extremely 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.

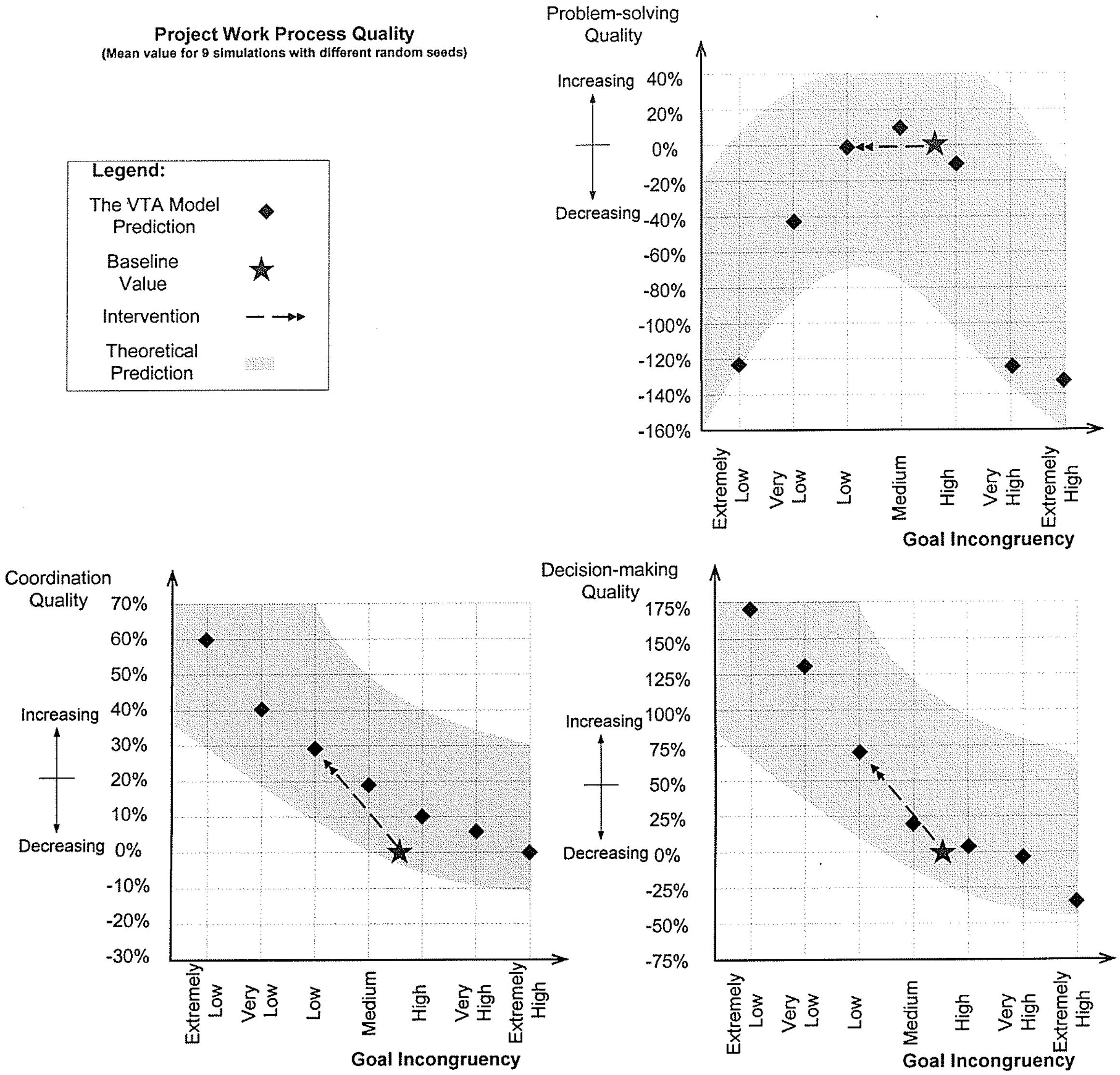

***Figure 4:* Simulated Work Process Quality vs. Goal Incongruency.** The three graphs show goal incongruency on the horizontal axes, and level of work process quality for our three measures on the vertical axes. In the same way as described in Figure 3's caption, we used the initial input model as a 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.

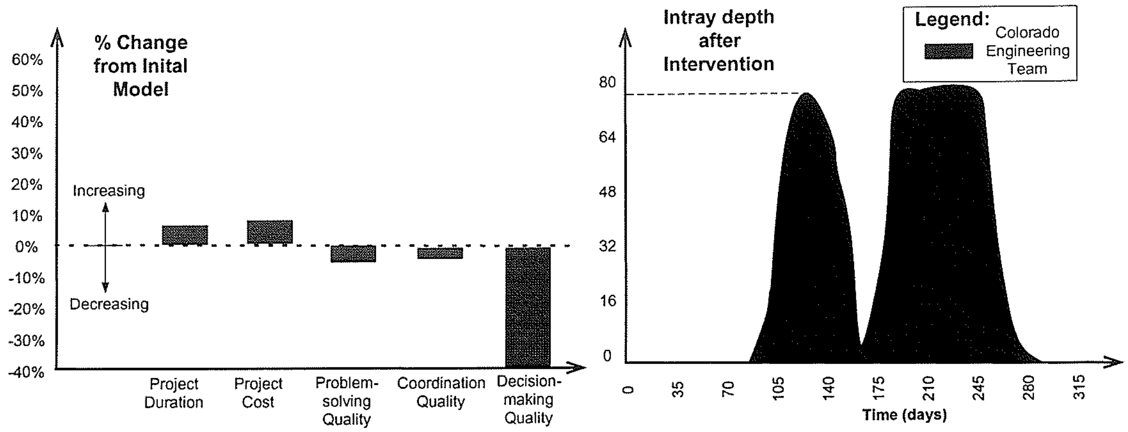

***Figure 5:* The Effect of Reallocating Attention to Old Communication.** The first bar chart shows the relative change in performance indicators by representing the project manager's intervention solely as changes in attention allocation distribution. The second diagram depicts the in-tray depths for 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.

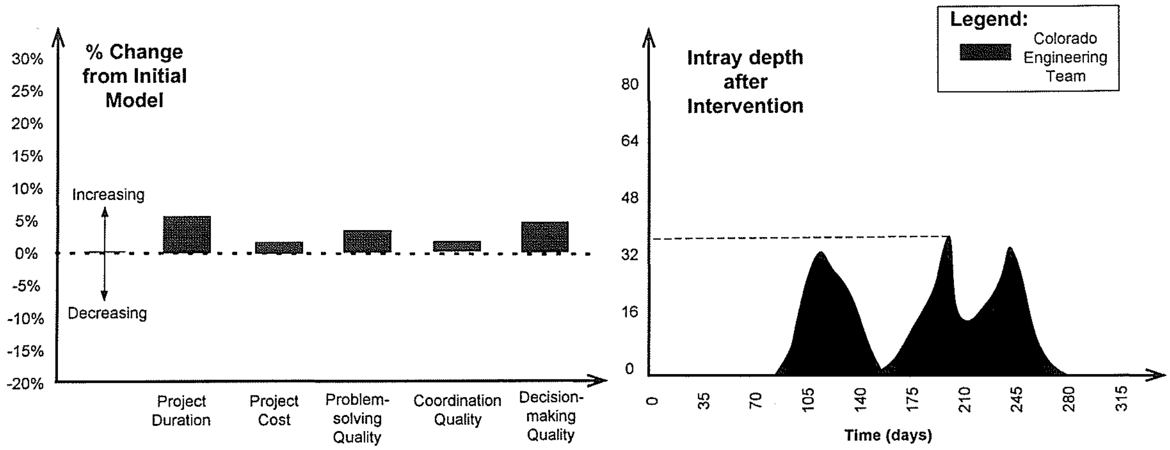

Figure 6: **The Effect of Shifting Priorities from Primary Work to Communication Work**. The first bar chart shows the relative change in performance indicators by representing the project manager's intervention as a focus made on more coordination work instead of primary work. The second diagram depicts 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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