



Management Science

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To cite this article:

Raymond E. Levitt, Jan Thomsen, Tore R. Christiansen, John C. Kunz, Yan Jin, Clifford Nass, (1999) Simulating Project Work Processes and Organizations: Toward a Micro-Contingency Theory of Organizational Design. Management Science 45(11):1479-1495. <https://doi.org/10.1287/mnsc.45.11.1479>

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Simulating Project Work Processes and Organizations: Toward a Micro-Contingency Theory of Organizational Design

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The Virtual Design Team (VDT) extends and operationalizes Galbraith's (1973) information-processing view of organizations. VDT simulates the micro-level information processing, communication, and coordination behavior of participants in a project organization and predicts several measures of participant and project-level performance. VDT-1 (Cohen 1991) and VDT-2 (Christiansen 1993) modeled project organizations containing actors with perfectly congruent goals engaged in complex but routine engineering design work within static organization structures. VDT-3 extends the VDT-2 work process representation to include measures of activity flexibility, complexity, uncertainty, and interdependence strength. It explicitly models the effects of goal incongruency between agents on their information processing and communication behavior while executing more flexible tasks. These extensions allow VDT to model more flexible organizations executing less routine work processes. VDT thus bridges rigorously between cognitive and social psychological micro-organization theory and sociological and economic macro-organization theory for project teams. VDT-3 has been used to model and simulate the design of two major subsystems of a complex satellite launch vehicle. This case study provides initial evidence that the micro-contingency theory embodied in VDT-3 can be used to predict organizational breakdowns, and to evaluate alternative organizational changes to mitigate identified risks. VDT thus supports true "organizational engineering" for project teams.

(Agency Theory; Concurrent Engineering; Coordination Theory; Contingency Theory; Goal Incongruency; Interdependence; Project Management; Project Organizations; Computational Organizational Design; Information Processing; New Product Development; Organization Design; Professionals; Semiroutine Tasks)

1. Introduction

Managers of fast-paced, highly concurrent projects in industries ranging from construction to semiconductors deploy project organizations comprised of distributed and often outsourced subteams to develop their complex new products. The ever increasing pressure to get products to market more rapidly has led many companies to “fast-track” their product development efforts, i.e., to take many activities that traditionally have been done sequentially and execute them concurrently. These concurrent projects pose the following managerial challenges:

1. *Activity Interdependence.* The activities involved in design and production of a complex product cannot usually be decomposed into truly independent activities (Simon 1996, pp. 197–204). When interdependent activities are executed concurrently, changes or errors that arise in one activity must be communicated to the participants responsible for all of the functionally interdependent activities. Interdependence creates coordination requirements that need to be managed.

2. The project team needs work process *flexibility* to come up with innovative solutions for tightened and challenging product performance requirements (Brown and Eisenhardt 1997). Participants cannot simply reuse methods or solutions derived from previous projects, but they try new approaches, some of which will turn out to be blind alleys. In concurrently executed projects, each change or error—called an “exception” (Galbraith 1973)—creates need for communication, decision making, and potentially extra direct work in the form of rework. Work process flexibility thus adds to coordination workload.

3. *Actor Goal Incongruency.* Organizations of multiple subteams inevitably include participants whose goals differ not only within a given subteam but also across subteams. Interdependent, goal incongruent actors may prefer different solutions. Actor goal incongruency thus compounds the coordination workload arising from activity interdependence and flexibility.

4. *Creative Tension.* Some exceptions enhance project performance. These “productive exceptions” will be more likely to occur where workers are more skilled in

particular areas than their managers. Creating “learning organizations” that experiment and innovate by seeking and exploiting this kind of creative organizational tension adds another layer of coordination workload for a project team to process.

CPM/PERT scheduling tools do not represent the “coordination and rework overhead” of executing flexible and interdependent activities in parallel. Thus, concurrent engineering can lead to severe cost overruns and schedule delays relative to the inherent optimism of CPM/PERT schedules for such projects. Moreover, when participants work heroic overtime in an attempt to meet unrealistic deadlines, quality breakdowns frequently occur. Witness Windows 95™ and the first release of Intel’s Pentium™ microprocessor.

Thus modern product development organizations have a daunting challenge: *Participants who may have incongruent goals, seek creative tension, and have limited experience working together must deal with high coordination and rework demands brought on by “concurrent” scheduling of nonroutine activities that are flexible and interdependent.*

The Virtual Design Team (VDT) framework (Levitt et al. 1994, Kunz et al. 1998) addresses the issue of coordination in concurrent projects. It models the organization, the work plan, and their relationships. It (stochastically) simulates the organization performing the activities, and it predicts both the direct and the coordination work for individual activities and the overall project. The objective of the VDT research program is to develop methods and tools to support true organizational engineering. Our vision is that engineers should be able to design their product development work processes and organizations in the same way that they already design their products—by modeling analyzing and evaluating “virtual prototypes” of the work processes and organizations, rather than by costly trial and error experiments on real organizations.

2. Relationship to Existing Theory and Tools

This research bridges between micro-organization theory derived from cognitive and social psychology on

the one hand, and macro-organization theory from sociology and economics on the other. VDT uses computational agents that have validated fragments of micro-organization theory as axiomatic or “canonical” building blocks. It models work processes as activities with attributes and relationships, including functional interdependence strength, that can be derived from the subgoals to which activities contribute. Then it simulates the actors executing their assigned activities, and attempting to resolve exceptions that arise from both their own activities and other actors’ interdependent activities by communicating and processing information.

The research can be positioned in relation to several streams of past or ongoing research. Critical Path Method (CPM) and Program Evaluation Review Technique (PERT) tools have proven useful in predicting schedules and in directing resources to critical activities on projects that sequentially execute functionally interdependent activities. However, they provide misleading and consistently optimistic predictions for highly concurrent product development projects (Moder et al. 1983). CPM/PERT models assume that concurrent activities are functionally independent and require no coordination. Critical Path Models also view project participants as always acting—but never interacting—in perfect harmony with the project plan. Finally, Critical Path Models assume there is a single deterministic way to perform the tasks on the project (although PERT simulation employs Monte Carlo simulation to model stochastic variation in activity durations). Thus, managers using CPM/PERT tools can predict neither the magnitude nor the specific locus of the increased coordination and rework overhead that will arise during execution of concurrently scheduled projects.

The Process Handbook initiative (Malone et al. 1999) describes best practices to manage classes of dependencies among work processes. Malone and his colleagues consider two major issues: representation of work processes and efficient and effective browsing through a database of these work processes. Malone et al. do not claim that their handbook will provide any prescriptions to the organizational designer or theorist. It can, however, store and retrieve work processes

from a library of processes used in other contexts to effect the same high-level purpose—e.g., taking orders from customers—and then help a user to elaborate and refine a high-level work process interactively for the user’s specific context. VDT can import and simulate work processes developed using the Process Handbook through the Process Interchange Format (PIF) that the VDT and Process Handbook research teams helped to develop (Lee et al. 1994).

Total Quality Management (TQM) gives general, universal suggestions, but not specific, quantitative, detailed, or contingent recommendations about how to change an organization to affect quality, cost, or duration (Deming 1982, Juran 1992, Crosby 1979). As Sitkin (1994) explains, the TQM approach does not consider the particular structure and environment of each organization. Thus, a manager must rely on intuition and experience in adapting the general principles to design an appropriate organization and project workflow in each situation.

In summary, Critical Path Models, Contingency Theory, Coordination Theory, and Total Quality Management lack theoretical foundations to predict the behavior of fast-paced, semiroutine project organizations following realistic changes in the plan or the organization. The primary contribution of this paper is an organizational design “micro-contingency” theory—i.e., a theory to describe and predict behavior at the level of individual actors and activities—that we operationalize into a computational organizational model. Our first generation Virtual Design Team frameworks (VDT-1 and VDT-2) modeled routine project work processes and organizations. VDT input includes required activities, organizational participants, and the assignment of participants to activities. VDT-1 and VDT-2 assumed that actors are in complete agreement about project goals (Levitt et al. 1994, Kunz et al. 1998). The VDT-3 framework described in this paper extends VDT in both theoretical and practical directions. VDT-3 represents a methodology and tool that allows organizational decision makers to engineer a fast-paced, semiroutine project work process, and the organization that will execute it, comprised of

multiple subteams and participants with varying degrees of goal alignment or congruency.

After laying out the foundations of VDT, we describe the conceptual framework underlying its representation and reasoning. VDT is assembled with elements of “canonical” information-processing micro-behavior derived from broadly accepted cognitive and social psychological research findings; we describe each of these micro-behaviors in some detail. Next, we present the results of a set of experiments in which we applied the VDT-3 simulation framework to an industrial project to provide initial validation of the model’s representation and reasoning. The paper concludes with a summary of the model’s practical and theoretical contributions, its limitations, and future research directions.¹

3. Foundations

Three basic types of computational models are in use today for analyzing the behavior of complex organizational systems—formal mathematical models, heuristic diagnosis models (Buchanan and Shortliffe 1984), and simulation models (Carley 1995). Mathematical models are of necessity abstract and parsimonious. This is both a theoretical strength and a practical limitation in using them to generate specific predictions. Heuristic Diagnosis models such as Burton and Obel’s (1998) Organizational Consultant provide an intermediate level of detail, but still typically use the entire organization as their level of analysis. In model-based simulation frameworks, quantitative or heuristic relations among variables are replaced with objects representing individual actors and small subteams interacting according to micro-theoretical assumptions in chains of events. We argue that these kinds of model-based simulations best represent the dynamic behavior of actual complex organizations because relevant objects—e.g., activities, participants, messages, meetings—from the real world are specifically represented by corresponding software objects with defined properties and behavior in the model.

¹ Readers who are unfamiliar with project management techniques and tools may wish to read the case study of the Lockheed Martin Launch Vehicle presented in §6 first, to provide a context for the theoretical discussion in §§1–5.

Organizational sociology offers a number of perspectives on how to view organizations, such as contingency theory (Lawrence and Lorsch 1967), the resource dependence approach (Pfeffer and Salancik 1978), population ecology (Hannan and Freeman 1977), and institutional theory (Meyer and Rowan 1977), among others. The structural contingency approach most directly relates organizational performance with different organizational factors (Thompson 1967). The literature it has spawned on organizational design offers some of the most prominent theoretical approaches to understanding organizational performance (Pfeffer 1996, p. 70). Examples of contingency factors include environmental complexity (Tung 1979, Jurkovich 1974) and environmental uncertainty (Lawrence and Lorsch 1967, Duncan 1972). The second precept is that all possible ways of organizing are not equally effective. Specifically, organizations that exhibit structures that fit the demands of their environment will be more successful than organizations that do not (Pfeffer 1982, p. 148). Since we hope to study the effects of different organizational structures on performance and quality, we use contingency theory as the starting framework for our model of organizational behavior.

VDT adopts the information-processing view of organizations first proposed by March and Simon in their seminal work *Organizations* (March and Simon 1993). The information-processing perspective has been the predominant framework used by structural contingency theorists to understand organizational behavior. Organizations are seen as sophisticated information-processing and decision-making machines that behave as if they have preprogrammed subroutines that are invoked appropriately. Jay Galbraith (1973) has shown, based on studies on the development of the Boeing 747, that March and Simon’s information-processing view can be used to describe product development efforts.

We follow Galbraith (1973, 1977) and Tushman and Nadler (1978) in conceptualizing organizations as webs of information processing nodes connected by communication channels. Information is processed at the nodes—i.e., by actors—and different types of

communications are passed between the nodes using a variety of communication tools (e.g., electronic mail, fax, phone, etc.). Internal behaviors available to actors include attention allocation, information processing, communication, and decision making.

For the purposes of our research, we have found it necessary to extend existing contingency theory and Galbraith's information-processing theory to create a sound theoretical basis for VDT. Galbraith and other contingency theorists focus on macro-organizational variables, and on behavior at the level of the entire organization. Thus, they cannot make specific predictions about meso-level variables or the internal dynamics of an organization. We have extended contingency theory to develop a "micro-contingency" model of organizational behavior. It takes the actor, activity, and the relationship between actors and activities as fundamental units of analysis.

Our initial VDT framework, VDT-1 (Cohen 1991) and VDT-2 (Christiansen 1993), can be viewed as modeling the "information flow physics" of organizations in much the same way as Newton's Laws of Motion provide an idealized model of the interactions between force, mass, and acceleration of bodies. VDT-3 adds the effects of goal incongruity between actors. This augments the VDT-2 information flow physics model with a modicum of "organizational chemistry" to extend the range of its applicability and to enhance its predictive power.

Interpersonal dynamics between individual actors can profoundly impact organizational performance and quality. We represent information processing and communication behavior associated with differing levels of goal incongruity at the level of individual actors, and incorporate it into the larger framework provided by Galbraith's information processing model. VDT-3 uses aspects of economic agency theory (Eisenhardt 1989) to represent and reason about the behavior of actors embedded in vertical dyadic relationships in the organizational hierarchy, and it uses social psychological theories dealing with goal incongruity (Weick 1979) to address the behavior of "peer" actors working on interdependent tasks.

The reason for this focus on a detailed level is to represent the interplay between activity interdepen-

dence and flexibility; goal congruity of actors; and the relative frequency of productive vs. nonproductive exceptions. This allows a user to:

1. Identify specific actors and activities that pose the greatest risk of schedule delays or process quality problems; and
2. Make specific predictions about the extent to which a potential organizational intervention will mitigate these risks.

We represent actors and activities as computational objects that have attributes and relationships to each other and have computational behaviors that implement the various organizational micro-behaviors. To examine the effects of different organizational designs on performance, we developed a framework to model organizational behavior. At the core of the object-oriented framework is a stochastic, discrete event simulation engine that generates emergent project behavior as actors carry out direct work, coordination work, and rework. We create alternative scenarios and use the simulator to predict the effects of alternative organization and work process designs on project performance. The user can vary a wide range of decision variables that characterize product performance requirements, work process sequences, human resource skill profiles, and organizational reporting structures.

The VDT simulator (stochastically) models the total information-processing capacity of an organization as the aggregate information-processing capacities of its nodes, modified by the efficiency of the communication network—comprised of vertical relationships defined by the formal structure, and emergent lateral relationships driven by activity interdependencies—that connects the nodes. The simulator computes the total information-processing load on the organization from the project requirements for direct work and coordination work. In the spirit of Tushman and Nadler (1978), organizational performance derives from the goodness of fit between the information-processing load on the organization and the organization's capacity to handle that load. For additional details of the VDT implementation see Jin and Levitt (1997).

4. Representational Constructs

The work process description holds a central place in the VDT framework. Activities comprise the work process description for a project, and actors do work and report exceptions through their hierarchical reporting structures. The project schedule becomes a shared view of the overall work process.

4.1. Representing the Work Process

VDT represents the knowledge work performed by an organization abstractly as a volume of information to be processed. Activities are assigned to actors that perform the work volume “contained in” those activities. The emphasis in modeling is on activity attributes and relationships that effect coordination load. Activity attributes and relationships drive the frequency of both exception generation within activities as well as the need for interaction between activities. VDT activity properties include *predecessors* and *successors*; a *responsible actor*; *activity work volume*; and the *principal required skill*.

In the organization contingency literature, activity uncertainty is treated as a qualitative variable describing the task environment faced by an organization as a whole (Duncan 1972, Lawrence and Lorsch 1967). We operationalize *activity uncertainty* at the activity level (rather than at the overall project level), and the simulator uses this attribute to affect coordination requirements among project actors.

Actors have limited rationality (March and Simon 1993). The more demanding the 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. 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 relationships as having strength, we are able to discriminate between the interdependence relationships for different pairs of activities, and can focus on those that are most important.

We developed a quantitative methodology to derive

activity complexity and interdependence strength between activities based on a project manager’s tangible knowledge of project requirements and activities.

4.1.1. Linking Activities and Requirements. An activity contributes to a requirement if solution approaches exercised within the activity affect the satisfaction of the requirement. The “contributes to” relationship between an activity and a requirement can be positive, negative, or nonexistent. Good project management practice suggests that each activity have a primary requirement that is the major focus of attention for that activity (Kerzner 1997). The activity positively contributes to this primary requirement in the sense that alternative solution approaches for the activity are evaluated by how well they satisfy this primary requirement.

4.1.2. Activity Complexity and Interdependence Strength Between Activities. 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 an 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 satisfies or does not satisfy 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 satisfies, the actor’s aspiration levels will drop until a satisficing solution approach is found (Soelberg 1967, Simon 1997b, pp. 323–324). In a manner similar to activity complexity, we can calculate two activities’ *interdependence strength* as the sum of the strengths (i.e., the requirement complexities) for all requirements shared by the two activities (Thomsen et al. 1998a).

4.2. Representing Organizational Participants

We assume that an actor’s competence determines the quality of actions carried out, and an actor’s prioritizing of goals suggests which actions will most likely be carried out.

Actors’ competence is measured by a skill set (a list

of discipline-based skills possessed by each actor at low, medium, or high levels) together with the actor's level of experience (high, medium, or low) for the current type of application.

In introducing actor goals to VDT-3, we wish to avoid the complexity of decision-theoretic or utility-based representations (Howard and Matheson 1983). Our approach is more descriptive than normative with respect to project goals. We are interested in information processing and communication micro-behavioral changes within the organization in response to the level of goal incongruity between actors, not in the actual approach that actors will use to meet product requirements, nor the product characteristics that will result.

In addition to a project's requirements, a number of overriding project goals constrains 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 have different personal goals and preferences. Thus, they may prioritize project goals differently and hence may favor different solution approaches to meet given requirements.

We developed a methodology for gathering data on goal incongruity within a project team based on Chatman's (1991) card-sort method (Thomsen et al. 1998a). We ask the project manager to list the most important project goals. Each project participant is then asked to sort a card-set of these project goals in order of priority. We calculate the distance in goal priorities—i.e., the level of goal incongruity—between pairs of project participants by simply summing the absolute differences between their respective rankings of the set of project goals.

In addition we measure the amount of length of time that the members of the team have been working together (described by the value of a "team experience" variable). Coordination can be largely implicit when team experience is high vs. more explicit otherwise.

5. Canonical Information Processing Micro-Behavior

VDT models and simulates two kinds of communication processes (exception handling and information exchange), and two kinds of decision making (attention allocation, and whether or not to do rework when an exception is detected). All of these actions consume time of the actors involved. VDT-3 represents micro-behaviors arising from goal incongruity using the two communication processes.

5.1. Exception Generation and Handling

As each work package is executed, the goal-oriented actor responsible for the work package may generate exceptions to the project plan, since it is boundedly rational (Simon 1956). VDT-3 exceptions are of two types—technical errors (TE) and nonconformances (NC). Technical errors arise 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. Nonconformances are exceptions that arise directly from goal incongruity between the manager and the subordinate. They are not incorrect from a technical standpoint (i.e., the final product will still meet its requirements if a nonconformance is not remediated); rather, they do not conform to the solution approach that the manager had prescribed or desired, and hence may result in a different trade-off among project goals than the manager would have preferred.

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. If the exception is a nonconformance, its probability of being a productive nonconformance (PNC) is affected by the difference in skill between the subordinate and the supervisor. A relatively unskilled supervisor will encounter primarily productive NCs from a highly skilled subordinate and vice versa.

An exception is forwarded to the appropriate supervisor that decides how to deal with the exception. In the cases of TE and counterproductive nonconformances, 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. As long as the decision maker makes a decision, the work process quality is unaffected, but the project cost and duration will change. We assume that the decision the actor makes is generally supportive of project goals, but reflects the actor's personal priority among project goals. Ignoring an exception is acceptable as long as the decision maker has made an evaluation of the consequences of the decision. However, whenever the decision maker becomes overloaded, it may not have a chance to detect the exception or make a decision. In this case, the actor waiting for the decision proceeds in a "default delegation" mode after a specified time period has expired. Default delegations reduce process quality.

If a large number of technical errors or nonconformances are undetected or not attended to, decision-making quality will tend to suffer. Correcting or reworking technical errors or counterproductive nonconformances will increase decision-making quality, but at the expense of cost and time. In contrast, productive nonconformances allow the project to terminate more quickly and efficiently, provided that they are not eliminated through rejection (i.e., a productive nonconformance can only be beneficial if the nonconformance is accepted by the supervisor and allowed to stand).

5.2. Selective Delegation of Authority

Selective authority delegation refers to the process by which managers determine how much decision-making power to grant to subordinates. Based on ideas from economic agency theory, we assert that 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.

A manager's perception of high levels of goal incongruency, as well as a propensity for micro-involvement on the part of the manager, will cause the manager to delegate less authority to subordi-

nates (Burton and Obel 1998). Thus, authority delegation to subordinates is negatively correlated with the level of goal incongruency and the manager's preference for micro-involvement.

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. Because of their global perspective, managers have a greater awareness of the severe ramifications that a failure in one activity could have for other interdependent activities. Hence, higher-level VDT actors are more likely to decide to perform rework, rather than to correct (i.e., do a "quick-fix") or ignore errors when exceptions are detected and vice versa.²

5.3. Information Exchange

In this section, we describe five well validated—hence "canonical"—micro-behavioral interaction processes that actors exhibit in response to goal incongruency: one for vertical relationships and four for lateral relationships. These responses are not necessarily mutually exclusive. The extent to which each one is invoked is contingent on the level of goal incongruency as well as other organizational factors.

5.3.1. Monitoring. Given that the VDT model is based on an information processing view of organizations, we represent managerial control mechanisms as processes of monitoring and the aforementioned selective authority delegation (Eisenhardt 1989). VDT-3 calculates the level of monitoring and delegated authority for each hierarchical dyadic actor supervisory relationship. It first considers the overall project level of monitoring and the degree to which decision making is centralized, and then by modifies these initial

² The cultural assumption that "higher level managers are more likely than their subordinates to rework errors" fits many kinds of hardware design organizations. However, this assumption had to be reversed to model the culture of a software development team. In this case, programmers wanted to fix all bugs, whereas the manager was willing to ship the software with known, nonserious bugs to meet a release date. These and other aspects of actor micro-behavior are specified in decision table form in a "behavior matrix" text file that is accessed by VDT at run time.

values locally 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 1998)—as well as the level of goal incongruity within each manager-subordinate relationship.

Monitoring in VDT-3 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 probabilistic 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 to deviate 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 VDT subordinates do not attend to managerial prescriptions (because they are backlogged with other direct work and communications), the probability that they will generate an exception increases, since the subordinate will not be aware of the new prescription and may inadvertently deviate from it. As more reports and questions are channeled up the hierarchy by subordinates, managers will become more aware of the status of work packages. This coordination will increase the probability that exceptions will be detected. However, when managers are backlogged and do not attend to coordination, the probability of exception detection will decrease.

As a rule, the perception of high levels of goal incongruity—as well as a propensity for micro-involvement on the part of the manager—will cause a manager to engage in more extensive monitoring. Perceived goal congruity will lessen the intensity of monitoring.

At the completion of each task, the VDT subordinate probabilistically reports to its supervisor, with a probability based on the level of goal incongruity between the subordinate and supervisor and 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 sends a message up to its own supervisor based on the goal incongruity between itself and the supervisor, as well as on the supervisor's preference for micro-management. Attending to reports increases the probability that exceptions will be detected.

All communication requires time of supervisors and subordinates. 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. On the other hand, this increase may be offset by a decrease in coordination quality when the hierarchy becomes overloaded with communications. It is clear that there will be some optimal level of hierarchical communication in each case—too little may result in an excess of exceptions as a consequence of goal incongruity, and too much may overload actors to the point that they become seriously backlogged. The latter is a particular concern for supervisors with large spans of control.

5.3.2. Peer Communication. A comprehensive model of organizational behavior needs to consider the lateral interactions between project members, in addition to the vertical, hierarchical interactions described above.

5.3.2.1. Steamrolling. Steamrolling is a process in which one actor appeals to a higher authority to force some other actor to perform an action. In VDT-3, steamrolling occurs only within interdependent relationships and is most prevalent in relationships with high goal incongruity. There is a probability that an actor will appeal to its supervisor through an external 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 incon-

gruency 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 its manager), then the actor that is the victim of the steamrolling will receive 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 tasks 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. In contrast, if the disparity in actor competencies is small, each actor is more likely to give greater weight to the opinions of the other and will be less certain that its own solution is categorically better than the other's. The actors are thus more likely to search for additional solutions and clarify goals to arrive at a satisfactory decision.

5.3.2.2. 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 length of time that the members of the team have been working together (measured by the "team experience" variable in VDT-3). Some history of association and collaboration is necessary for actors to expect and 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 most pronounced when there are low levels of goal incongruency between actors. As the level of goal incongruency increases within highly experienced teams, members will begin to resort to alternative means of resolving differences 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 nonconformances 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 nonconformances will increase acutely for high levels of goal incongruency.

5.3.2.3. Searching for Alternatives and Goal Clarification. In VDT-3, the processes of searching for alternatives and goal clarification 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 mutually acceptable solution. Goal clarification likewise increases the volume 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 has been 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 to find a mutually acceptable solution to the problems at hand. The more alternatives 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 VDT-3 is to increase

the volume of communication. When communications are well attended to, the number of productive nonconformance 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 productive global solution.

However, at very high levels of goal incongruity, the number of productive nonconformances will decrease because the interdependent actors are less likely to find mutually productive solutions. The increase in peer communications and the u-shaped effect on number of productive nonconformances 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 to consider. The effects of goal incongruity on peer communications and productive nonconformances 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 the recipient actor ignores communications aimed at resolving goal incongruity, 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.

The above discussion explained how the VDT-3 simulation represents micro-behavioral assumptions associated with the level of goal incongruity between vertical and lateral actor dyads. It showed how VDT-3 simulates these behaviors as the actors (1) execute their assigned activities, and (2) interact with other actors in the project organization to coordinate interdependencies or to handle several kinds of exceptions, thereby generating emergent macro-outcomes for the project team.

6. Analysis of an Agile Organization

We applied the VDT-3 model to a number of test cases (Thomsen et al. 1998a, 1998b, 1998c). It is not feasible to report on all of the contexts and results of several multiyear, multiperson case studies within a single

journal article. In this section, we summarize the results from a launch vehicle development project that provided the initial validation of the representation and reasoning employed in VDT-3. We refer the interested reader to Thomsen et al. (1998c) for additional details about the validation experiments conducted for VDT-3.

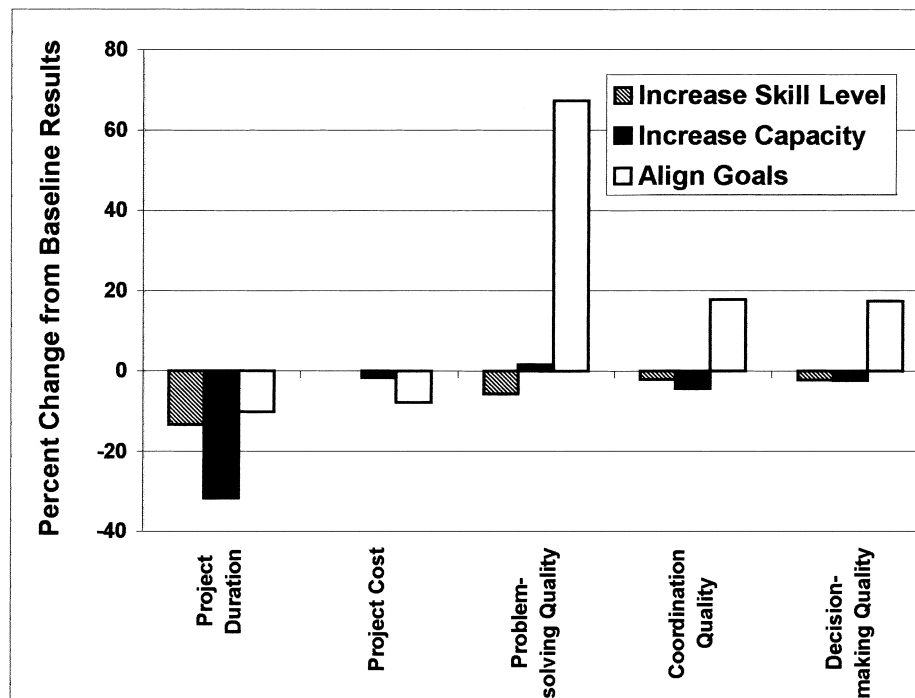
6.1. Launch Vehicle Development

This case study was conducted in an aerospace company that has over 25 years of experience developing missiles to launch weapon systems. The introduction of a new commercial launch vehicle program in 1993 marked a major effort to adapt the firm's missile technology to build commercially viable, versatile, and reliable launch vehicles for commercial satellites. Much of the work was outsourced to external component suppliers whose team experience and goal congruity with respect to the prime contractor varied. The launch vehicle program is made up of various Product Development Teams. We modeled two teams—Avionics and Structures—and did our modeling and analysis contemporaneously with project execution (Thomsen et al. 1998c).

Our simulation results from the Avionics and Structures teams can be divided into two categories. The first set of results involves the straightforward predictions made by VDT-3 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 "intellective simulation" experiments (Burton and Obel 1995) in which VDT-3 predicted the likely performance of the project teams, given particular managerial interventions.

The dynamic VDT-3 simulation of the Structures team did not predict any significant deviation from the original project plan. Subsequently, the development team had no significant coordination problems. However, the model for the Avionics team predicted a severe risk of coordination bottlenecks within two of its subteams—the Cables subteam and the Flight-Boxes subteam—that would significantly increase time and cost, and increase quality risk for the project. Of the two, the overload on the Cables subteam was greater. Subsequently, the Cables subteam encountered significant coordination problems, and there

Figure 1 VDT-3 Predicts the Effects of Three Organizational Changes on Project Duration, Cost, and Process Quality Outcomes for the Avionics Product Development Team



were significant subsequent engineering product quality problems with cables.

Figure 1 summarizes VDT-3 predictions of the percentage changes in five measures of project performance from the baseline plan, arising from three organizational changes to the existing project scenario:

1. *Increase Skill Level*. The baseline scenario, with participants in the *Cables subteam* given a “high” (vs. medium) skill level;

2. *Increase Capacity*. Baseline scenario with the *Cables subteam* capacity increased from three FTEs to five FTEs);

3. *Align Goals*. Baseline scenario after use of a goal alignment program to decrease the average goal incongruency level between project participants.

For each scenario, the chart shows five different project performance metrics: *Project duration* (i.e., elapsed time along the longest “critical” path through the CPM network of activities), including direct work, coordination, and rework. Increasing subteam capacity significantly shortens project duration. Both increasing skills

and aligning goals reduce the predicted duration, but significantly less than increasing capacity.

1. *Project Cost* (i.e., the total work-hours spent to perform direct work, coordination and rework for all project activities). Skill and capacity interventions have no significant effect on predicted cost; goal alignment helps marginally.

2. *Problem-Solving Quality*. The ratio between [(productive nonconformances) minus (technical errors and counterproductive nonconformances)] and [total number of exceptions]. Goal alignment significantly improves predicted problem-solving quality in comparison with the baseline or other interventions.

3. *Coordination Quality*. (the number of attended communications) divided by (the total number of communications). Again, goal alignment significantly improves predicted coordination quality in comparison with the baseline or either of the other interventions.

4. *Decision-Making Quality*. The ratio of (the number of exceptions decided upon by the appropriate actor in

a timely manner) to (total number of exceptions). Again, goal alignment significantly improves predicted decision-making quality.

Increasing actor skill levels results in faster actor processing speeds and reduced predicted risks of both project and functional errors. This intervention shortens duration; it has no effect on cost (higher monthly salary costs are almost exactly offset by reduced project duration in this case); and it has minimal effects on quality, since the baseline level of goal incongruity is unchanged. As in the baseline case, goal incongruity causes peer-to-peer information requests to go unanswered, and leads managers to centralize decision making and monitor subordinates closely.

The second strategy, increasing subteam capacity, primarily effects predicted project duration. In this case, the saving in duration is more than enough to offset the cost of the extra resources for this subteam, so that cost is slightly reduced. As with the first intervention, predicted quality is essentially unchanged for the same reason: goal incongruity continues to effect communication quality.

The third intervention, aligning goals, dominates the other strategies in this case. By reducing the need for monitoring and supervision, this streamlines decision making and saves predicted time and cost, although it does not save as much time as increasing subteam capacity. By facilitating peer-to-peer communication and reducing the probability of steamrolling, politicking, and goal clarification behaviors, goal alignment enhances all three measures of process quality. Supervisors whose goals are aligned with their subordinates are more likely to accede to productive nonconformance requests. Goal alignment thus contributes to significantly higher problem solving quality. Since this organization has low formality, there are many ad-hoc information requests generated between information-dependent actors. A higher level of goal alignment increases the likelihood of actors responding to each others' ad-hoc information requests, thereby raising coordination quality. Decision-making quality is a measure of whether decisions are made by the appropriate actors. With higher levels of goal alignment, supervisors both delegate more deci-

sions to be made by subordinates; and they spend less time monitoring subordinates so that they can make the decisions that they should make. Both effects contribute to decision-making quality.

It is clear that for all three potential interventions, there are distinct trade-offs between the five variables measuring project performance. Different interventions (e.g., increase capacity) will maximize project performance according to one indicator (project duration), but may negatively affect other measures of project performance related to quality. Hence, before determining whether to promote or discourage an organizational design strategy within the team, a manager must assess the relative importance of each performance indicator. If the Avionics team manager assigned the highest priority to project duration, then the preferred intervention would clearly be to "increase capacity." Similarly, assigning the top priority to project cost or any of the quality measures would suggest choosing "align goals" as the preferred strategy. In this case study, cost and quality goals were paramount, so the "align goals" intervention was indicated. To reduce the level of goal incongruity, the Avionics manager could either have brought in new participants with more congruent goals, or set up goal alignment and team building processes with the current set of project participants.

6.2. Lessons Learned

Because of outsourcing commitments already made, and a lack of sufficient prior experience with the modeling methodology, project management did not intervene in the Avionics product development process based on the VDT prediction. The backlog and its impacts later appeared 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 safety officials detonated the vehicle, along with its commercial payload. The launch vehicle's instrumentation system provided extensive analog and digital data, enabling detailed analysis of the two anomalies.

The subsequent analysis revealed two anomalies that caused loss of the launch vehicle: The first anomaly occurred 80 seconds after lift-off, when the vehicle

suddenly pitched nose up. The pitch-up occurred because a misrouted 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 lift-off. 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*).

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*).

7. Discussion

The intuitive notion that the quality of an organization's work process affects the quality of its ultimate product has also been demonstrated convincingly by researchers in the facility engineering domain, most recently by Fergusson (1993). Hence, models like VDT, which generate predictions of process quality in specific activities, can indicate the levels of risk for product quality problems in particular subsystems. The VDT-3 analysis predicted severe backlog problems in both the Cables and Flight-Boxes subteams. The disastrous result of the first launch was judged *ex post* to have been caused by problems in the areas of responsibility of these same Cables and Flight-Boxes subteams. The results from this case study, therefore, reinforce the wealth of accumulated evidence that product quality derives from process quality; and they provide initial evidence for the predictive power of the information-processing micro-contingency theory embodied in VDT.

Contributions

Traditional project management tools, macro-contingency theory, coordination theory, and TQM are of limited practical help in developing and evaluating alternative fast-paced, semiroutine organization and process designs. Our

representation and computational approach allow us to capture detailed knowledge about the project and to model the root causes of interdependence strength—and hence coordination loads—easily and consistently. We focused, first, on describing a representational scheme because clear representation makes knowledge acquisition easier. Second, we linked our representation to information processing behavior within the VDT discrete-event simulator. Third, we illustrated the usefulness of the VDT model on a launch vehicle development project contemporaneously with project execution. VDT-3 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. For a second structures team on the same project, VDT-3 predicted no problems, and none occurred.

Our 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 (skill set, application experience, team experience, and goal incongruency) in semiroutine, fast-paced projects within the framework of organizational contingency theory. Our representational framework can be used without computational simulation for “intuitive simulation” by the project manager and as a tool for disseminating information that identifies and characterizes potential risk areas to project participants.

VDT extends existing organization contingency theory (Thompson 1967) and Galbraith's information-processing theory (Galbraith 1973, 1977; Burton and Obel 1998). Galbraith and other contingency theorists focus on organizational behavior at the level of the entire organization. We have extended contingency theory to develop a micro-contingency model of organizational behavior. VDT uses actors, activities, and the relationships between actors and activities as the fundamental units of analysis. As a result, our micro-contingency theory provides predictions and supports interventions in terms of real-world organizational design decision variables that managers can manipulate directly.

Our contribution to TQM lies in the development of a conceptual framework and a computational organi-

zational model founded on the information processing view of organizations that can model and predict an organization's quality performance (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). In line with Sitkin et al. (1994), our detailed contingency approach challenges this assumption and takes into consideration specific characteristics of an organization's work process, hierarchy, personnel makeup, and environment in predicting process quality micro-contingently. VDT moves the focus of quality management from measuring and controlling process quality one step up the causal chain—i.e., measuring and controlling the quality of the organizations that execute processes.

Limitations

A project must have relatively clear goals to be modeled and simulated in our framework. Project managers should understand work processes well enough so they can relate requirements to a set of predefined activities, and can assign these activities to specific actors (specialized individuals or subteams) for execution. Third, the activity model should be at a level of abstraction for which exceptions to prespecified activities can be modeled as simply adding to or subtracting work from these activities. While these restrictions are not appropriate for all projects or organizations, they fit many engineering design and product-development tasks. Moreover, VDT can be used to model many kinds of operations in organizations that are moving to "reengineer" their ongoing work processes as "projects" (Hammer and Champy 1993, Davidow and Malone 1992).

Today's "agile organizations" impose greater tension regarding time-quality trade-offs. VDT can represent such tensions through goal incongruity between project participants. However, in VDT-3, goal incongruity is static—that is, there is no change in goal incongruity over the course of the project. Such a view of goal incongruity is limiting, since people adapt their 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. An extended model of

goal incongruity would account for learning and adaptation by individuals and would view goal incongruity as a dynamic variable.

Future Research

Our VDT research to date has focused on 20th century hierarchical organizations executing semiroutine work processes in projects. Over the next few years, we intend to augment VDT's information processing model of project organizations with newer ideas about how problem resolution and exception handling for nonroutine work can be facilitated through constantly evolving "communities of practice" or "knowledge networks" (Monge and Contractor 1999). In so doing, we hope to build from a platform of 20th century organization theory to invent new theory and analysis tools for diagnosing and designing the vastly more dynamic and adaptive organizations that will be needed by firms to compete in the global economy of the 21st century.³

³ The National Science Foundation, Transformations to Quality Organizations program, Grant SBR-9422389, provided financial support for this research. Lockheed Martin Corporation provided an exceptional level of access to data and participants in the Lockheed Launch Vehicle Project. The authors gratefully acknowledge the contributions of these organizations to the research.

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Accepted by Richard M. Burton; received June 1994. This paper has been with the authors 37 months for 2 revisions.