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Abstract

This article describes the early stages of the "Virtual Design Team" (VDT) research program, whose long range goal is to develop computational analysis tools for organizational (re)engineering. The work described here is aimed at developing, testing and calibrating theory that can eventually support systematic organizational analysis. We lay out the requirements for a micro-contingency theory of organizations and conclude that such a theory is tractable for routine, project-oriented design tasks. We describe a specific micro-contingency theory that operationalizes Jay Galbraith's well-known information processing framework, and adds to it ideas about attention allocation. This theory models the ability of organizations engaged in routine, project-oriented tasks to handle the information processing load arising from direct work and coordination. We implement the theory as a computational symbolic model that simulates boundedly rational actors carrying out information processing tasks. The framework explicitly models actors, activities, communication tools and organizations. We use a structured methodology to analyze the organization's task in order to specify activity complexity and uncertainty, and interdependence between organizational actors. Using these attributes to model the coordination load imposed on the organization by a given design project, the simulation framework generates measures of overall project duration, cost, and coordination quality as emergent from work by, and communications between, actors. We present results of three empirical tests of the computational model on large-scale, capital facility projects. We found three-way qualitative consistency among predictions of the simulation model, of organization theory, and of experienced project managers. The results of these initial attempts to validate VDT indicate that the model has the representational power to capture aspects of organizational information processing load and capacity that could not previously be modeled. In addition, VDT's detailed micro-contingency framework can make qualitatively correct predictions about organizational efficiency and effectiveness.

(ORGANIZATION THEORY; ORGANIZATION DESIGN; INFORMATION PROCESSING; SIMULATION; ARTIFICIAL INTELLIGENCE; SYMBOLIC MODELING; COORDINATION THEORY; COLLABORATION TECHNOLOGY)

1. Introduction

Faced with increasingly competitive global markets and increasingly tight-fisted taxpayers, many private and public organizations are now "(re)engineering" their organizations to improve their products or services significantly and to reduce time between receipt of a new order and delivery of the requested product or service to a satisfied customer. When managers change existing work processes to reduce schedules dramatically, interdependent activities which were previously performed sequentially must be performed concurrently. Organization theory predicts that coordination of concurrent interdependent activities is significantly more difficult and costly than coordination of the same activities performed sequentially. Yet traditional organization theory can neither predict the magnitude nor the specific locus of the required incremental coordination effort.

This paper describes results from the first stage of the Virtual Design Team (VDT) research project, an ongoing program of research to develop computational analysis tools for organizational (re)engineering. This paper summarizes and synthesizes the Ph.D. thesis work of Cohen (1992) and Christiansen (1993) which were aimed at formulating and testing a micro-contingency theory of information processing load and capacity in concurrent engineering organizations.

1.1 How Schedule Compression Affects Coordination Load—A Case Study

A case study illustrates the problem of estimating coordination load and capacity for an organization and shows how the Virtual Design Team (VDT) framework might be used to address it. The Statfjord Subsea Satellites Project (Christiansen 93) was undertaken in the early 1990s to produce oil from deep ocean wells in the Norwegian sector of the North Sea. The goal of this project was to design, manufacture and place unmanned subsea oil production modules on the ocean floor. Since they would be expensive to access once placed, the Statfjord modules were designed to very high quality standards to ensure that they would operate reliably, maintenance-free, for extended periods. After this project started, its work plan was "re-engineered" to reduce its development schedule from 3 years to 2 years. To fit this new schedule, the project's design time was reduced from 22 months to 15 months. The resulting schedule was "radically concurrent."

To evaluate the feasibility, benefits and costs of the proposed schedule reduction, the clients, financiers and managers of the Statfjord project needed answers to questions such as the following:

- Could the original design team complete the design within 15 months, instead of 22 months? If not, which specific design disciplines or management groups should be augmented?
- What detailed changes, if any, could the manager usefully make in the organization structure of the 25-person design team—e.g., decentralization of certain design approvals or decisions?
- If decision-making authority were decentralized to save design time, what would be the impact on other aspects of project performance—e.g., on rework volume, design cost or product quality?
- What would be the predicted impact on project schedule of investing in advanced communication technologies —e.g., CAD file sharing or video conferencing?

We explain in the following section why neither extant organization theory nor network-based project management techniques can make the detailed predictions needed to answer these questions. Thus, Statfjord's managers had to rely on their experience and intuition to provide answers to these important questions.

We used VDT to model the Statfjord project. We derived the information processing and coordination loads of the 15 month design task, using the coordination load modeling approach described in Section 2.3. We represented the project's organization structure and policies based on interviews with Statfjord's project managers. Using the model for qualitative "What-if?" studies, we then varied two dimensions of the organization structure—centralization and formalization—and compared the simulation results to predictions of managers and of the underlying theory.

Galbraith's (1977) theory predicts that duration should increase if the organization changes to more centralized decision-making. For this project, we found qualitative consistency among the simulation prediction (increase of 4% in duration between lower and higher centralization), the project manager's prediction (increase of 17%) and theory. Theory predicts that process quality should also increase if decision-making is changed from decentralized to centralized. The simulation model calculates two measures of process quality: verification quality and communication quality. Again, the simulation prediction about the impact of centralization on verification quality (decrease of 28% in number of uncorrected non-conformance), the manager's prediction (decrease of 50%) and theory are all qualitatively consistent. This and other validation studies have allowed us to validate the VDT framework and to begin calibrating the variables that affect its quantitative predictions.

This case study illustrates the way in which we imagine VDT and its successors might begin to fill the gap in providing theory and modeling tools to answer detailed questions about the impact of schedule pressures, organization structure and project policies on several measures of task performance.

1.2 Limitations of Extant Theory

Engineering Management tools such as the Critical Path Method have been consistently shown to make overly optimistic predictions about project duration. The "merge-event bias" inherent in deterministic network representation of tasks is one well-known reason for this (Moder & Philips, 1983). Merge-event bias can be overcome by stochastic simulation of networks using techniques such as PERT simulation. However, we suggest that a second source of bias in network-based scheduling tools arises from the fact that they typically only represent direct tasks; coordination tasks are usually implicit in such models. Thus, these tools tend to underestimate the impact of added coordination complexity on project duration.

At the same time, organizational "contingency theory" (Thompson 1967; Galbraith 1977; Mintzberg 1979) can provide only limited answers to the questions posed in the previous section, in the form of aggregated and qualitative predictions about how increased task interdependence, with the same or a different organization structure, might affect organizational performance.

Work process re-engineering generally leads to shortened schedules and more task concurrence. The initiators of work process (re)engineering efforts thus face the same dilemma as project managers: Before implementing changes aimed at improving a process, they must predict the specific performance consequences of alternative task breakdowns, organization structures, and investments in information systems and communications technologies. Thus, we argue, there is a need for a "micro-contingency theory of organizations" to answer questions about the effects on organizational performance of changes in task requirements, actor capabilities, organization structure and policy, and communication tools.

1.3 VDT Goals

We began the Virtual Design Team (VDT) research program in 1986 with the long range goal of developing organizational analysis tools. However, the user of an analysis tool must have faith in the validity of the theory upon which it is based. Thus, our first stage research goal is to develop and validate a "micro-contingency" organization theory that describes and predicts specific behaviors of alternative organizational designs under specified task requirements. We expected to build this theoretical framework by operationalizing and extending extant contingency theory.

To develop a testable theory, we decided to implement the theory in a computer simulation model. The framework of [Burton 1993], lays out four kinds of simulation:

descriptive simulation, intellective or quasi-realistic simulations, normative simulations and man-machine simulations, each having different purposes for which there are appropriate levels of modeling detail, and appropriate experimental design and data analysis plans.

Our long range goal is "normative simulation," i.e., detailed descriptive modeling of alternative scenarios for a given task and organization, and the use of simulation predictions associated with alternative input variables to select a preferred organization structure. We see our research program as generating a time path of simulation efforts with different purposes. We began by developing an operationalized version of Galbraith's theory and tested this intellective simulation model by comparing its results against the predictions of Galbraith's theory [Cohen 1992]. Next, we used the internally validated framework to perform descriptive simulation of an existing organization—a large team designing an oil refinery. Here, we compared the VDT-1 model predictions with the predictions of experienced managers. In the second phase of the research, we developed a new theory of coordination to develop a quasi-realistic simulation model of the coordination process in concurrent design as an extension of the original VDT-1 model [Christiansen 1993] and compared its results to the predictions of the underlying theory. Then we cycled back to descriptive simulation, using Christiansen's internally validated VDT-2 framework to model two real projects, comparing the model's predictions to the predictions of experienced managers. In all of these cases, the projects were large and almost completed, and natural experiments were not possible.

We expect to continue the cycle of quasi-realistic ("intellective") simulations each time we add new theory to the model, followed by descriptive simulations to validate and calibrate the framework externally. When the model is sufficiently comprehensive, and has been validated and calibrated, it can be used to analyze real tasks and organization structures prescriptively.

2. Toward a Micro-Contingency Theory of Project Organizations

Organizational Engineering is the process of configuring an organization structure to accomplish a given task while attempting to satisfy stated performance objectives. An organization includes human actors supported by information processing and communication tools.

In the organizational literature on contingency theory, coordination load is the complex set of requirements for coordination among the various actors in an organization. It is usually reduced to a single, ordinal measure of the level of interdependence among actors in the organization: *High, Medium* or *Low*. This organizational convention is analogous to a structural engineers' view of the complex set of gravity and lateral loads acting on a building as a single, aggregated "point load" applied to the center of gravity of the building. Structural engineers commonly use the point load abstraction to make a first-order analysis of the overall stability of a building's structural system. Such an analysis might indicate that a particular structure will be stable for a given set of loads, e.g., that a given medical office building will not overturn in a Richter magnitude 7.0 earthquake. However, the analysis provides no assurance that individual members comprising the structure will all have acceptable stresses—e.g., that the floor slab in the radiologist's suite on the 10th floor will support the X-ray photograph file cabinet through the same earthquake. Even more important in practice, the point load assumption cannot check that the member connections will transfer loads adequately. Many catastrophic failures of physical structures, such as the tragic Kansas City Hyatt Regency catwalk collapse (Marshall 1982), result from the failure of over stressed connections, not from the failure of undersized structural members or overall structural systems.

The structural engineering analogy illuminates and motivates our approach to organizational modeling. Like its structural engineering counterpart, the organizational "point coordination load" abstraction has proven to be useful for making aggregate predictions about the impact of overall organizational structure on organizational performance at the level of the firm, given an overall characterization of the task and environment. However, to support organizational (re)engineering, we want to identify the limits of specific components of a proposed, reengineered organization so that we can anticipate and prevent future problems. Thus, a manager wants to predict the overall and local performance of a set of actors (c.f., "structural members"), supported by specific communication tools ("load-transferring connections") in a given organization structure ("structural system"), under a detailed and distributed set of coordination loads. In short, we need a "micro-contingency theory" of organizations, and we want to operationalize, validate and use it.

A micro-contingency theory of organizations must model the information processing capacity of actors and the information processing load imposed on them by a given task. The VDT capacity model represents activities, actors, structure, communication tools and information exchanged among actors at a relatively fine grain size. It generates specific predictions about available information processing capacity at every node and the available information transmission rate through every channel of the organization.

The following sections discuss the characteristics of task domains that such a micro-contingency theory might tractably address and summarize our extension of Galbraith's (1977) information processing framework to provide an operationalized and executable *information processing capacity* model of a project organization.

2.1. Criteria for Selecting a Task Domain to Model

A useful way to characterize task domains for our purposes is to assess the degree of clarity in their goals and means or processes (Thompson 1967). An organization with ambiguous or contested goals will have difficulty assessing its performance, even *a posteriori.* If it understands its processes poorly, an organization will have difficulty formalizing its work processes and making rational trade-offs among goals, no matter how clearly the goals are defined.

To be amenable to analysis in a micro-contingency theory, a task domain should have, first, relatively clear and uncontested goals. Second, organizations in this domain should understand work processes well enough that a manager can relate goals to processes and can assign activities to different, specialized individuals or subgroups. In addition, if executed, the process should have a high probability of satisfying the organizational goals. Third, the interactions among subgoals must be derivable from the organization's breakdown of its overall task into subgoals and activities to achieve them. We presume that subgoal interdependence is important because it leads to interdependencies among the specialized actors assigned to accomplish particular subgoals, and hence to requirements for actors to coordinate with each other.

While these criteria do not apply to all organizations, they apply well to many engineering design and product-development tasks. As traditional mass manufacturers or service providers move toward ever shorter production runs of increasingly customized products and services, they are organizing their ongoing work processes as a series of "projects", each with well-defined internal or external "customers", with clearly defined goals, and often with well-understood technologies (Davidow 1992). In these well-structured semi-custom manufacturing or service domains, the well-understood direct work processes can be modeled as critical path networks of sequentially interdependent activities with relatively predictable durations. At the same time, formalized techniques such as Quality Function Deployment (Hauser and Clausing, 1988) are useful for decomposing high level product goals into specific customer requirements and for analyzing interactions among requirements to derive needed coordination activities. We can thus explicitly represent information processing load arising from the direct work, and from required coordination, for such organizations.

As a starting point for VDT, we chose to model the design of capital facility projects that are complex, but routine or "semi-custom." Examples of such projects include design of power plants, petroleum or petrochemical refineries, and offshore oil platforms. This domain has a number of attractive properties for our purposes:

- Task complexity is only moderately high. Highly trained professionals and paraprofessionals perform the direct work with minimal supervision.
- Actor interdependence is very high in multidisciplinary facility design tasks. Customer-, site- or producer-driven variations in subsystems for each design case generate the need for extensive coordination of decision making by the interdependent discipline specialists if the design is to meet specifications and subsystems are to be compatible.
- Coordination failures can have serious consequences. They can lead to design rework if detected before manufacturing begins, to more expensive physical rework if detected during installation, and to potential catastrophic failure during subsequent facility operation if undetected.
- Interdependence between actors is high. Moreover, fast-track schedules add to the already high levels of interdependence among actors in concurrent design projects, since fast-tracking leads to overlap of design and construction activities, and even to overlap of a major portion of the design process with construction.
- Work processes are highly institutionalized for engineering design (Meyer and Rowan 1977). The institutional determinants of designers' behavior include professional education and registration of engineers; building and other codes of practice; environmental, safety and labor laws; company standards and handbooks; and requirements for verification of compliance, e.g., ISO 9000 (Ticket, 1992).

Exploiting these properties of the chosen domain, the Virtual Design Team model:

- Abstracts away the technical engineering content of the direct task work that each specialist carries out, since it is only moderately complex, and is so highly institutionally regulated as to be essentially "invariant" with changes in organization structure or coordination tools;
- Explicitly represents actors, communication tools, activities, and organizations, including both their attributes and their relationships among each other;
- Explicitly represents the coordination actions needed to integrate the work of specialists assigned to the various subsystems comprising the project; and
- Incorporates attention rules by which actors select the information processing and coordination tasks to which they will allocate their scarce attention.

2.2. Information Processing Load Model

The information processing load on each actor in an organization arises from a combination of *routine* and *exceptional* work (Galbraith, 1977). If the performance of each actor's specialized work is relatively routine and formalized, then it is reasonable to model information processing requirements simply by the time that they take to complete.

Coordination activities, which often interrupt direct work activities, constitute the majority of exceptional work for actors in our model.

Christiansen integrated a set of engineering management techniques into a structured methodology to specify the amount of required coordination between each set of actors based on the requirements of the activities assigned to each actor. We review the methodology briefly in this section and in Figure 1; Christiansen (1993) describes the modeling methodology in detail.

Functional Decomposition (FD) provides a means for creating a hierarchy of customer requirements and their associated technical solutions in an intended product design Willems (1988). We use the FD approach to develop a complete set of product requirements and solutions for use in a Quality Function Deployment (QFD) analysis Hauser and Clausing (1988). We then use QFD analysis to identify the interdependence among activities based on the assumed technical interactions among their requirements and solutions. We also use QFD to specify the complexity of each activity by analyzing the number of interacting requirements and solutions associated with that activity. The Design Structure Matrix (DSM) technique (Gebala and Eppinger, 1991) analyzes the information flow among interdependent project activities and assesses the relative uncertainty associated with the requirements of each activity based on the sequencing of the activities. We use these techniques together to specify complexity and uncertainty levels of each activity. The simulation checks activity complexity and uncertainty levels as it sets activity duration and generates coordination requirements.

As shown in Figure 1, an activity is VDT's unit of analysis for modeling task-related issues including information processing requirements, activity interdependency, complexity and uncertainty. The coordination requirements for the responsible actors are then inferred from these activity attributes.

2.3. Modeling Information Processing Capacity

Jay Galbraith's (1977) information processing view of organizations provides a foundation for modeling the information processing patterns of an organization and, by simulation, for determining overall information processing capacity of an organization. Galbraith views organizations as limited in their ability to process "exceptions"—requests for advice or direction when local knowledge or authority is insufficient to deal with the information processing requirements posed by an actor's task. The organization's information processing capacity, in this view, is limited both by the bounded rationality (Simon 1976) of the actors or "nodes" in an organization and by the limited information carrying capacity of the information "channels" that connect actors.

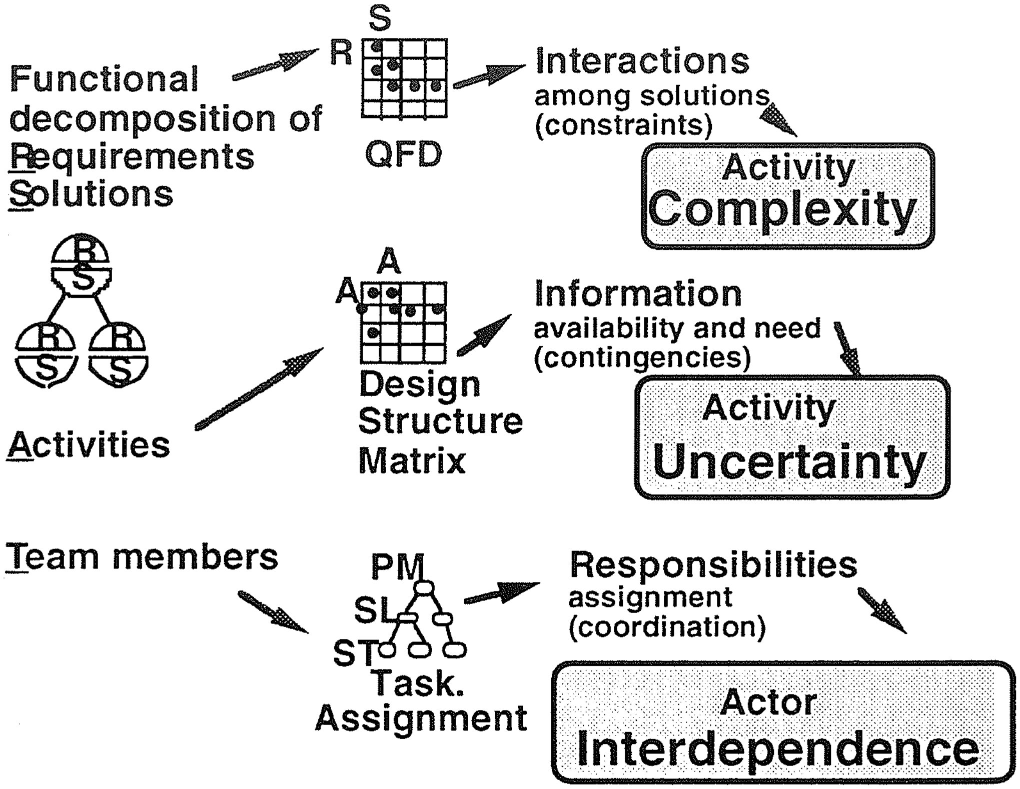

Figure 1. The VDT Work Load Model. We use standard techniques to specify values for activity complexity and uncertainty, and actor interdependence attributes. These derived attribute values are inputs to the VDT capacity model, shown in Figure 3. "PM" refers to project manager; "SL" refers to subteam leaders; and "ST" refers to subteams.

Galbraith's theory provides a qualitative process model that predicts why high-level managers' "in-trays" can become organizational bottlenecks in the face of high task uncertainty, high activity interdependence and centralized decision making. Galbraith suggests that information overload in an organization can be dealt with in two organizational ways and one strategic way:

- *Reduce its information processing load* by (1) decentralizing decision making to autonomous subunits and (2) choosing looser performance requirements—analogous to increasing "organizational slack" in Cyert and March's (1963) "Behavioral Theory of the Firm".
- *Increase the information processing capacity* of an organization by (1) increasing the information processing capacity of "vertical" hierarchical channels through such devices as the use of standard symbols—jargon—to encode information into higher level chunks, enhancements to the management information system; or staff assistants to managers, and (2) progressively formalizing channels for lateral

communication. The latter strategy ignores the classical management theorists' exhortations to respect unity of command.

- *Negotiate with the environment to reduce uncertainty*: We have not yet considered this strategy—which includes supply chain management—in our work.

Nadler and Tushman (1988) subsequently turned Galbraith's framework into the beginnings of an explicit micro-contingency theory by asserting that the goodness of fit between the *information load* and *information processing capacity* of an organization determines its effectiveness. Thus, the Galbraith/Nadler and Tushman framework provides the conceptual underpinnings of the kind of micro-contingency theory that we assert is needed.

The Galbraith framework, although conceptually suitable for our purposes, is too aggregate and qualitative to support organizational engineering. To generate specific predictions about information processing capacity versus load at the level of individual actors or subunits, we extended Galbraith's framework in a number of directions. Specifically, in VDT, we:

- Shift the object of analysis from an aggregated organization with a high level task to individual actors and their assigned activities.
- Compute organizational behavior and performance by simulating actions of and interactions among individual actors as they perform their assigned activities;
- Explicitly operationalize both definitions and attributes of organizational concepts including actors, activities, communications among actors, communication tools, and organizational structure;
- View actors as boundedly rational information processors in the spirit of Galbraith (1977), but also endow actors with boundedly rational attention allocation behavior;
- Relax Galbraith's assumption that all exceptions are undifferentiated information processing load, to be added to each actor's ongoing information processing load of non-exceptional work, and model each actor's information processing load as consisting of direct work, several kinds of coordination work, and noise, each having dynamic priorities for the actor's attention;
- Introduce notions of task verification and failure—specifically that tasks can "fail", that actors' responses to task failures depend on organization structure and policies, and that actors' responses to task failures affect the quality of the work process; and
- Extend Galbraith's (1977) notion of communication channels by modeling them as relationships among actors, each supported by one or more communication tools whose functional attributes affect the timing and quality of information transfer across that channel.

We discuss details of these extensions in the next section.

3. The Virtual Design Team: A Micro-Level Information Processing Model of Organizations

The basic premise of the VDT model is that organizations are fundamentally information-processing structures—a view of organizations that dates back to Weber's work in the early 1900s, and that is elaborated in (March and Simon 1958), (Simon 1976), (Galbraith 1977). In this view, an organization is an information-processing and communication system, structured to achieve a specific set of tasks, and comprised of limited information processors termed "actors"—individuals or undifferentiated specialist sub-teams. Actors send and receive messages along specific lines of communication (e.g., formal lines of authority) via communication tools with limited capacity (e.g., memos, voice mail, meetings, etc.). To capture these characteristics and constraints, VDT employs explicit descriptions of tasks, communications, actors, tools, and structures. Thus, for example, each modeled manager has specific and limited (boundedly rational) information processing abilities; and managers send and receive messages to and from other actors along pre-specified communication channels, choosing from a limited set of communication tools. Figure 2 presents the VDT view of organizations.

3.1. Activities

The VDT task model represents an organizational task, such as a design project, as a network of activities with sequential dependencies. As shown in Figure 2, when an activity is to be processed by the simulator, responsibility is assigned to a specific responsible actor. The simulator sends the actor work tasks (in the form of communications to the in-tray of the responsible actor) when the activity is ready to start.

Each activity requires an actor with appropriate skills to spend a certain amount of time to accomplish it. As discussed in Section 2.1 above, we have chosen to focus on tasks that are only moderately complex and highly regulated. In order to model as little detail as possible about activities but still retain the desired accuracy of performance predictions, we model the information processing requirement of an activity in terms of *work volume* and *work type*. Work volume is the time needed for an actor with average skills to complete the activity. Work type is the specialized skill or "craft" an actor must possess to carry out the activity effectively. Activities in VDT are composed of indivisible components called tasks. A task is the minimum amount of work that can be determined to have "failed". The simulation "clock tick" or unit of duration in VDT is typically one minute; the duration of each task is typically one day, or 480 minutes.

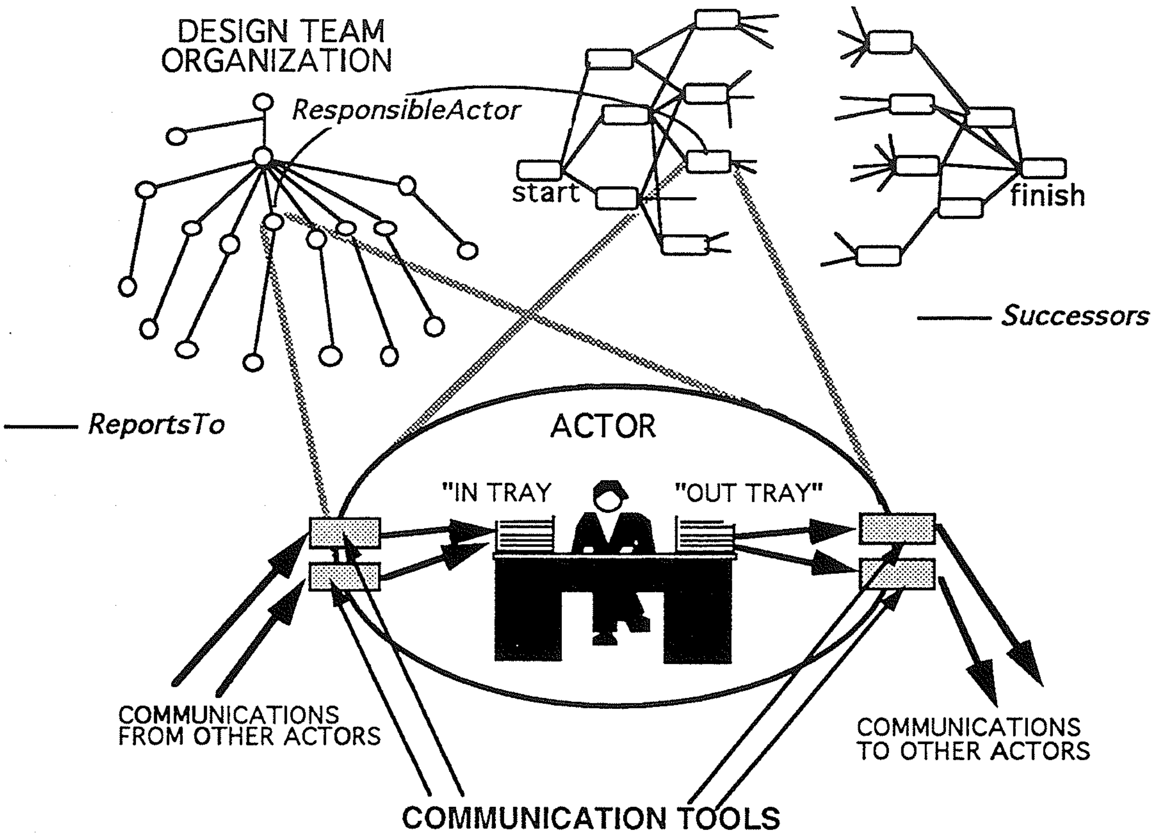

Figure 2. Overview of the Virtual Design Team Simulation System. The VDT load model (Figure 1) assigns values to some attributes of the actors in the design team organization, activities, and tools. The dynamic simulation behavior determines the model output concerning organizational effectiveness and efficiency, as shown in Figure 3.

Using these activity attributes together with activity precedence relationships abstracts much of the content of activities, but still allows the simulator to address matches among activities and actors, to separate work information processes and coordination processes, and to derive task efficiency and effectiveness based on actor and activity performance. Based on a match between the *complexity* of an activity and the *capability* of its responsible actor (described below), VDT model assigns an *actor processing speed*— a coefficient to be applied to the activity's nominal duration—and a *verification failure probability*—the probability that each task comprising the activity "fails" in the verification that occurs as it is completed.

Following Thompson (1967), VDT models pooled and sequential interdependence relationships among activities. We add the concept of functional interdependence among activities. Since we are concerned with relatively complex projects, we assume that all activities have at least *pooled* interdependence with each other; consequently, the performance of each contributes in an additive way—i.e., it consumes cost and time—to overall organizational performance. Activities can also be *sequentially* interdependent if the successful accomplishment of one or more activities is a prerequisite for another activity to start. In addition, activities can be *functionally* interdependent with one another if information produced by one activity must be communicated to another activity. In the case of failure of an activity, rework may (stochastically) cause rework in the functionally interdependent activity. These dependency relationships are important, first, because they define the patterns of information and control flow among activities. Second, from these relationships we can derive the coordination requirements among actors and the ripple impact of failure and attendant rework on other activities. Functionally (or "reciprocally") interdependent activities are identified through the QFD analysis described in Section 2.2.

Contingency theorists have characterized tasks in terms of complexity and uncertainty (Galbraith 1977; Thompson, 1967). In the organization literature, complexity and uncertainty are treated as variables describing the task environment faced by an organization as a whole. In VDT, we operationalize the concepts of complexity and uncertainty at the activity level (rather than at the overall project level), and use these attributes to determine the coordination requirements among actors. Higher activity complexity results directly in higher task verification failure rates and indirectly in more communication to initiate rework following task failures. Higher uncertainty of activities results in more information exchange communication among responsible actors. Uncertainty and complexity values are derived for each activity by analyzing the design team's product and planned activity sequence, as described in Section 2.2, and are assigned one of the values: high, medium, or low.

VDT's task model explicitly represents coordination requirements, unlike conventional CPM activity models. Thus, in addition to sequential dependency relationships among activities, VDT models coordination requirements in terms of *verification failure probability* arising from activity complexity, and *information exchange communication intensity* arising from activity uncertainty and interdependence. The former determines the probability that a task will fail when the simulator verifies the work of a responsible actor at the end of each task; and task failure leads directly to communications about failures among actors. The communication intensity defines how frequently the actor responsible for an activity needs to communicate with the actors responsible for functionally interdependent activities. During the simulation, coordination tasks—i.e., exception processing and communication—emerge as a result of direct work by actors.

Additional activity attributes include:

- Nominal duration;
- Precedence relationships that name Predecessor and Successor activities;
- Natural idiom (explained in the following section).

3.2. Communications

Coordination requires information flow among actors in a project team. A *communication* represents a "packet" of information that is generated and sent by one actor, and received and processed by another. Communications may be: *work communications* or *coordination communications*. The latter are further subdivided into *information exchange communications, failure exception communications,* and *decision communications.*[2]

The simulator creates work communications that inform each responsible actor when an activity is ready to be worked on by that actor. Using attention rules explained in Section 3.4, actors select tasks or exceptions from their in-trays to process. Upon selecting a task to process, the actor stochastically initiates information exchange communications to other actors based on the communication intensity and the reciprocal interdependence relationships of the activity on which (s)he is currently working. An information exchange can be a request for coordination or a "for your information" message.

When a task is completed—typically at the end of a work day—the task is stochastically verified to determine whether it has failed. The simulator generates failure exceptions when actors encounter failures in their task verification. As detailed in Section 3.4, generation of a failure exception initiates an exception-decision process. A decision communication is created after a manager has made a decision about what to do about an exception.

Although different types of communications may hold different information, they all share some common attributes: time stamp, author, recipient list, natural idiom, associated work volume, and priority.

Not all communications are of equal importance for the completion of a given task. Each communication is assigned a priority (on an integer scale from 1-9) by VDT based

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[2] VDT can also model non-task-related communications which we term "noise." Processing noise consumes actors' time without contributing to task performance.

on the relative status of sender and receiver and the type of communication. The receiver's attention rules may consider priority in deciding how quickly to attend to it.

A communication 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 a telephone dies after one minute if it is not attended to (adding voice mail changes this). When a communication exceeds its lifetime, the simulator removes it from the actor's in-tray.

Communications are also characterized in terms of their primary *natural idiom* from among a set of natural idioms used by engineers: *text, spoken voice, schematics* (i.e., two dimensional, iconic, topological representations of engineered systems such as circuit diagrams or piping and instrumentation diagrams), and *Geometry* (i.e., three dimensional CAD models).

3.3. Communication Tools

Galbraith proposes that actors or nodes in an organization are connected by information processing channels. VDT actors also have relationships such as "supervised by" and "reciprocally interdependent with". Communication tools allow actors to exchange communications across these relationships. Thus a channel in the Galbraith sense is a relationship supported by one or more communication tools in VDT.

Most existing organization theory treats communication tools as nominal variables. In contrast, VDT models functional attributes of communication tools after Nass and Mason (1990). Communication tools in the VDT model include face to face meetings, telephones, voice mail systems, scheduled meetings, and facsimiles. All communication tools have the following attributes: *synchronicity* (synchronous, partial, asynchronous); *cost* (low, medium, or high); *recordability* (whether or not a permanent record of the communication is available routinely); *proximity to user* (close or distant); *capacity* (number of messages that can be transmitted concurrently); and *bandwidth* (low, medium or high) representing the capability of the tool for communicating information represented in each of the *natural idioms supported* (i.e., text, schematics, etc.).

For example, voice mail is partially synchronous, low cost, recordable, close proximity, high capacity for concurrent transmission, and high bandwidth for spoken voice, but low bandwidth for text, schematics or geometry. Telephone is similar except that it is synchronous, not recordable, and has low capacity for concurrent transmission. In contrast, electronic mail is asynchronous, has high bandwidth for text and has high capacity for concurrent transmission. Thus, a manager who wants to send a textual communication to a large number of individuals simultaneously will choose a tool such as voice mail or electronic mail rather than the telephone. In contrast, the need for synchronous communication (arising from priority) will encourage the use of the telephone as opposed to the other two tools; and a communication to coordinate dimensions or layout of components—i.e., its primary natural idiom is geometry—will likely be sent by facsimile or CAD file sharing, rather than telephone.

3.4. Actors and Information Processing

Because of its aggregated view of organizational information processing, the Galbraith framework says very little about how actors' attributes influence their information processing behavior. We model project teams as comprising a set of "actors" that can be either individual managers and engineers, or small, subteams with undifferentiated members. Actors in a team are the entities that perform work and process information. By disaggregating organizations into actors and explicitly modeling their behavior, VDT generates emergent meso-level organizational behavior and performance resulting from the actions of, and the interactions among, individual actors.

VDT models actors in terms of their *capability*, *attention rules*, *action* and *organizational role*. Actors are rendered boundedly rational (Simon 1976) by limits on their information processing capability and attention rules.

3.4.1. Actor Attributes

Actor attributes include *discipline* (e.g., civil engineer, mechanical engineer, or project manager), *skill level* (high, medium, or low for each discipline), *task experience* for a given class of task (high, medium, or low), and *team experience* with other team members (high, medium, or low). The capability of an actor is modeled abstractly as the actor's information processing speed for the given activity. VDT represents an actor's information processing speed as an internal variable, *actor processing speed,* computed from the actor's task and team experience and the match between the actor's discipline and skill level versus the activity's discipline requirements.

For example, civil engineers will work slowly when assigned to a task with mechanical engineering skill requirements, even though their civil engineering skill level may be very high. We further assume that actors with higher levels of task experience and team experience work at faster rates (since they spend less time figuring out their activities' requirements, and spend less time coordinating with other actors, respectively).

Another important attribute that governs an actor's behavior is the actor's organizational *role* in the project team. In a design team, a VDT actor may play a role of project manager, sub-team leader, or designer. (Other roles can be defined for, e.g., software development teams.) In large design teams, a subteam of multiple specialists from a single discipline can be modeled as a single actor with the role of "designer", and a processing speed that is the sum of the subteam members' speeds.

Actors playing different roles reside at different levels of the team's organization structure (defined by *supervised-by* relationships among actors). Actors have different levels of authority for decision making depending on their roles and on the level of centralization of the team's decision making. The organizational role of an actor also determines the actor's rework decision-making behavior. We assume that project managers tend to demand more rework on failed tasks, whereas subteam leaders and designers or design sub-teams are more likely to ignore the failure of tasks and proceed without doing rework.

Additional actor attributes include:

- *Coordinates-with:* other actors with whom this actor will share information informally;
- *Location:* the recipient's *vs.* sender's location affects the choice of communication tools;
- *Supervises* and *supervised-by:* defines the hierarchy for exception handling; and
- *Preference:* for using each of the available communication tools.

3.4.2 Actor Behavior

Actors in VDT have several kinds of behavior. Actors:

Allocate attention—Activity start requests and communications accumulate in the in-tray of an actor to await processing. The actor's attention rules determine whether to interrupt an ongoing activity when a new communication enters the in-tray, and they select a new communication to process from the in-tray when a task or exception is completed. Based on the limited observations of design team managers conducted by Cohen (1992), VDT actor attention rules consider factors such as current activity priority, incoming communication priority, and the order in which communications enter the in-tray. VDT's default actor attention rules select the highest priority item 50 percent of the time; they use LIFO and FIFO each 20 percent of the time; and they randomly select a communication from the in-tray ten percent of the time.

Process information—After an actor selects a task or coordination item from the in-tray, VDT calculates the time required to process it based on the actor's processing speed (derived from the degree of the match between the attributes of an actor and the communication) and the work volume of the communication. During the time that an actor is processing a work task (typically about one day in duration), an incoming communication may arrive from another actor at each simulation clock tick, typically one minute apart). Whenever this occurs, the actor applies its attention rules and stochastically chooses whether to stop processing the current task to attend to the exception or communication.

Send communications to other actors—Coordination among actors is accomplished through communications. Actors in VDT communicate with each other by sending informal communication items or by attending scheduled, formal meetings. To send a communication to another actor, an actor must select a communication tool. Actors use several criteria for choosing a tool, including actor preference, message priority, primary natural idiom in message, proximity of sender to recipient, and cost.

Generate and handle exceptions—VDT actors generate, communicate and process several kinds of exceptions. These are detailed in the following section.

3.5. Exceptions and Decision-Making

Actors' task-related information processing and exception handling form the kernel of the VDT micro-contingency theory framework. Since we abstract much of the content of the design task, information processing related to direct design work merely consumes time of VDT actors. Processing exceptions, in contrast, requires VDT actors to route exceptions to authorized actors, who then make decisions about how to handle them.

Task failure is one kind of exception. A task is the smallest portion of an activity that can be evaluated—typically a day's work for an actor. Each task is verified when completed. This requirement is realistic for many kinds of engineering work, especially for design of highly regulated facilities such as power plants or offshore oil platforms. Verification can be performed via a simple peer review, a review by a supervisor, or an extensive client review if the task's completion results in completion of a key activity.

When the verification process evaluates a task as having "failed", the simulator generates an exception for the responsible actor. The responsible actor must decide (stochastically) with whom to communicate to resolve the task failure exception, based on the level of centralization of the organization. The actor then sends the exception to the authorized decision maker for resolution. When and if the recipient's ("decision maker's") attention rules select the failure exception for processing, the decision maker decides whether the failed task will be reworked, or whether the responsible actor should proceed without rework. The actor's rework rules, which vary for actors with different roles, determine probabilitistically what the rework decision will be.

If the VDT actor that initiated the task failure exception does not receive a decision after waiting for a given period of time, it assumes "delegation by default" and decides locally whether to rework or ignore the failed task. We assume, based on our observation of design teams, that engineers are more likely than their managers to ignore failures and to proceed without rework. Thus, if the managers authorized to make rework decisions in a project team are overloaded, rework decisions will tend to be delegated by default, designers will tend to perform less rework to correct identified failures than the managers would have preferred, and design quality will suffer. We discuss process quality measures in more detail in Section 3.6.

Requests for information represent a second kind of "exception." VDT models two different type of requests for coordination: *informal information exchange* and *formal, scheduled meetings*. Depending on the level of uncertainty of a given task (as measured by the DSM approach described in Section 2.2), its responsible actor will initiate informal information exchange requests to obtain needed information more or less frequently with actors performing interdependent tasks. Formal meetings are scheduled by the project manager. Meeting requests are generated by VDT and sent to participating actors to "remind" them about formal meetings and request their attendance.

We assume that the probability of responding to requests for informal coordination depends on an aspect of organizational culture—the "strength of the matrix" (Davis & Lawrence, 1977). By matrix strength we mean the extent to which actors are located in discipline-based functional departments and supervised directly by functional managers ("weak matrix") *vs.* co-located with other discipline specialists in dedicated project teams and supervised by a project manager ("strong matrix"). VDT assumes that the co-located actors in the strong matrix will be more likely to attend to informal communications; actors in a weak matrix will be culturally biased toward communicating in formal, scheduled coordination meetings.

3.6. Organizational Performance Metrics

As indicated above, VDT views the time and attention of its actors as the key resources of an organization (March 1988), and it measures organizational efficiency and effectiveness by looking at how these resources are consumed.

The *efficiency* of a project team can be measured by the project duration (i.e., the elapsed time along the longest or "critical" path through the network of activities) and the project cost (i.e., the total work-hours spent to accomplish all activities involved in the project).

Measuring the *effectiveness* of a project team is somewhat more difficult. Since VDT does not model the engineering content of products, it cannot judge the quality of the final product. Instead, we measure project effectiveness in terms of how well task failures and coordination requests are dealt with by actors.

When a task fails, the organization may or may not detect the failure. If the failure is detected, the organization can respond in ways ranging from completely reworking the failed activity and all related activities to ignoring the failure and proceeding directly with future tasks. We take the position that detection of task failure is not in itself an indicator of poor quality; rather it is the organization's response to detected failures that determines the *verification quality* of its work processes. We view the proportion of detected failures that get reworked as a measure of the quality of an organization's work processes.

Another, more subtle, aspect of process quality is the extent to which requests for coordination among interdependent actors are attended to. If actors are so busy that requests for coordination lie unattended in their "in-baskets" then interdependent tasks will receive inadequate coordination. The proportion of attended requests for coordination will thus be viewed as a second measure of process quality—*coordination quality*—that VDT can generate.

Thus, VDT generates two metrics to characterize the quality of the organization's work processes—verification quality and coordination quality. The notion that the quality of an organization's work processes affects the quality of its ultimate product—in this case, a capital facility—has been demonstrated convincingly by several researchers in the facility engineering domain, most recently Fergusson (1993). Fergusson's research is representative of a strong trend in all industries to move quality control upstream from measurement and control of completed products to measurement and control of the work processes that generate these projects.

We assert that VDT's approach of predicting process quality from the fit between task and organization structure is a logical next step up the chain of quality control—i.e., we propose to measure and control (analyze and design) the quality of the organizations that generate work processes that, in turn, produce products.

3.7. Organization Structure

One of the fundamental questions to be answered by organizational modeling is how changes in organization structure affect the organization's performance. Since organization performance in VDT emerges from simulated actions of, and interactions among, actors, we chose to address this question by identifying organization structure variables that control or influence actors' behavior. Thus, in VDT, organization structure affects organizational performance by enforcing behavioral constraints on individual actors.

Organization structure in VDT is defined by attributes of and relationships among actors. VDT differentiates formal control structure and information communication structure. A *control structure* is represented as a hierarchy of *"supervised-by"* relationships among actors, and has a certain level of centralization defined by organization policy. *Supervised-by* links guide actors to determine with whom they should communicate when a task fails; and the *level of centralization* determines at what level of the hierarchy a specific decision should be made.

For example, in a highly centralized organization structure, most decisions about rework are made by project managers. Thus, when an engineer detects an exception, the actor reports the exception to the sub-team leader, and the subteam leader passes the exception to the project manager for a decision. In a decentralized organization, decisions for many exceptions are made by the subteam leaders or even by the engineers themselves. Therefore, in a decentralized organization, fewer communications are sent to and processed by high-level managers. Decentralization reduces both the need for communication and the need for information processing.

Actors' *coordinates-with* relationships define who can coordinate with whom. We derive values for the coordinates-with relationships among actors from activity interdependencies as explained in Section 2.2. If activity A is *reciprocal-with* activity B, then their responsible actors are linked via *coordinate-with* relationships. A highly formalized organization relies on scheduled formal meetings for coordination and reduces the frequency of informal inter-actor information exchange requests. A less formalized structure increases the frequency of communications requesting informal information exchange.

Whereas an attribute of organization structure—formalization—affects the frequency of requests for informal coordination, an attribute of organization culture—matrix strength—affects the likelihood that a request for a formal meeting or an informal information exchange will be attended to. Since actors in functional or "weak" matrix organizations are not co-located, they tend to rely more on formal meetings to achieve coordination. Actors in weak matrix organizations, therefore, tend to prefer attending scheduled meetings over *ad hoc* information exchange. In contrast, co-located actors in strong matrix cultures learn to coordinate informally, and are thus more likely to decide not to attend formal coordination meetings. We view matrix strength as an attribute of organizational culture since it reflects actors' preferences for formal versus informal information exchange.

In summary, the frequency with which information communication links will be used to send and respond to coordination requests depends on aspects of both organization structure and culture—*formalization* and *matrix strength*, respectively.

3.8. VDT Implementation

The VDT system was implemented as an object-oriented, discrete event simulation. Projects, activities, actors, communications, and communication tools are all implemented as objects, or data structures that store both the state and the behavior of the concepts they represent. VDT actor behavior is often stochastic. VDT's discrete event simulation of stochastic behavior uses Monte Carlo simulation in which random numbers are compared to probability intervals to determine outcomes. For example, actors stochastically choose items to attend to from their in-trays and decide whether or not to communicate with interdependent actors upon completion of each task. The level of the hierarchy to which a request for a rework decision is sent, and the outcome of the rework decision are also determined stochastically by Monte Carlo simulation.

Version 1 of VDT (Cohen 1992) was implemented in KEE and SIMKIT, IntelliCorp's Lisp-based object oriented programming environment. For Version 2 of VDT (Christiansen 1993) we used Kappa, a C-based object oriented programming environment developed by IntelliCorp. The model was developed and the simulations were run on Sun Workstations. A single run of VDT for a large project (50 activities, 20 actors, one year project duration, one day task size) generates upwards of a million simulation events and takes about 15 minutes on a Sun SparcStation IPX.

4. VDT Validation

VDT extends contingency theory by focusing on individual activities and actors and treating organizational behavior and performance as emergent from the actions of and interactions among actors. In developing these extensions, we have introduced assumptions including new representations of tasks and organizational policy, and new models of actors' attention allocation, information processing and coordination behavior.

Our research sought to answer two questions through a formal validation process. Could we:

- Develop a modeling language and framework with sufficient expressiveness and power to represent and reason about project tasks and teams using variables that contingency theory considered important and for which project managers could provide values?
- Use the framework to predict organizational performance that matched the aggregate predictions of the underlying theories and the predictions of experienced project managers?

4.1. Research Design for Validation Experiments

Figure 3 shows our basic validation methodology. We differentiate three kinds of variables:

- *Case description variables* define a given project. They are held constant throughout a suite of simulation runs, e.g., attributes of communication tools;
- *Independent variables* define test scenarios and are changed during an experiment, e.g., the decision making policy of an organization (centralized or decentralized); and
- *Dependent variables* are outputs of each simulation run and change as a function of the independent variable settings, e.g., cost, duration and process quality.

We validated the simulation model by carefully observing three separate industrial projects. In each case, we designed a set of experiments in which we varied one or two independent variables and fixed the others at typical values, usually "medium". To average the stochastic simulation behavior, we ran three to five simulations for each experiment with different random number seeds and took the mean values of dependent variables as the results of that experiment. Significance levels of results for each validation case were analyzed with standard ANOVA statistical techniques.

For each experiment, we interpreted contingency theory and predicted the direction of change in the relevant performance measures, given the planned change in values of independent variables. We then compared the results from simulation and theory.

4.2. Predict impact of tools and structure on duration

For a first test case, we tested predictions about project cost and schedule. We modeled a three-year, petroleum refinery design project having a total design and construction cost of approximately $130 million, a planned duration of 20 months and, at its peak, approximately 120 design managers, engineers and support staff located in two offices. We derived all actor and task attribute values, attention rules and communication tool selection rules based on interviews with project managers. We held values of case description variables constant during the various runs of the VDT simulation. We selected two independent variables for this test case: *level of centralization of decision making,* and *presence or absence of voice mail.* Our interpretation of Galbraith's contingency theory, described in Section 3, predicted that decentralizing decision making and adding voice mail should each decrease the project's duration.

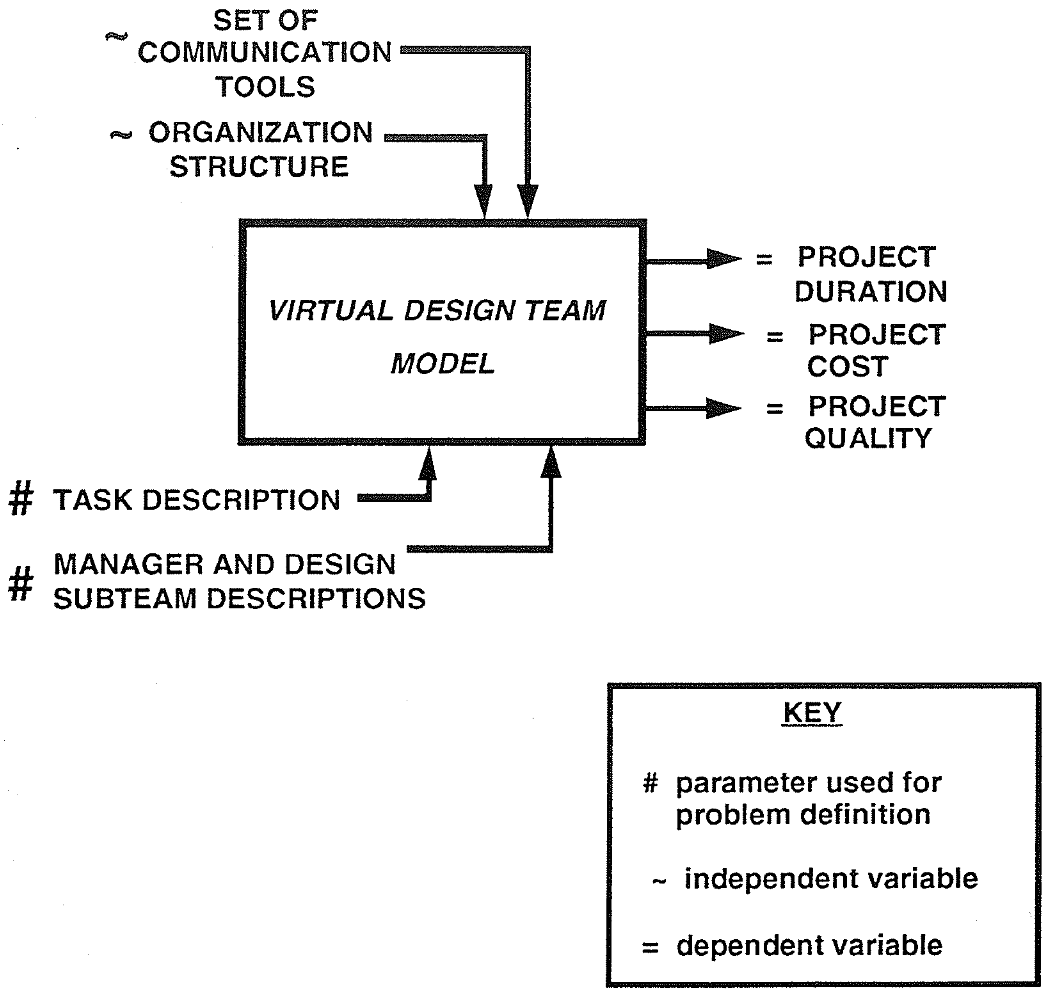

Figure 3. VDT Coordination Capacity Model Architecture. Given values for independent input variables that describe a project, the VDT capacity model simulates each task being performed and computes overall project duration, cost and coordination quality. We used the load model, schematically represented in Figure 1, to derive inputs to the VDT capacity model.

Our candidate organization had a decentralized structure and provided voice mail to its designers. To model a more centralized structure, we changed the level in the hierarchy to which verification exceptions were routed from subteam managers (decentralized) to design manager (centralized). In the base case, actors had voice mail. To remove voice mail capabilities, we reset the synchronicity attribute of the telephone tool from partially synchronous to synchronous, the recordability attribute from recordable to non-recordable, and the capacity attribute from high to medium. Values of all other variables in the model were set to an average value such as "medium." This form of sensitivity analysis is based on the method of Box and Hunter (1978), and was also used by Masuch and LaPotin (1989). We ran four sets of independent simulation runs to represent the four scenarios described by high and low values of centralization, and voice mail *vs.* no voice mail. The results are summarized in Figure 4.

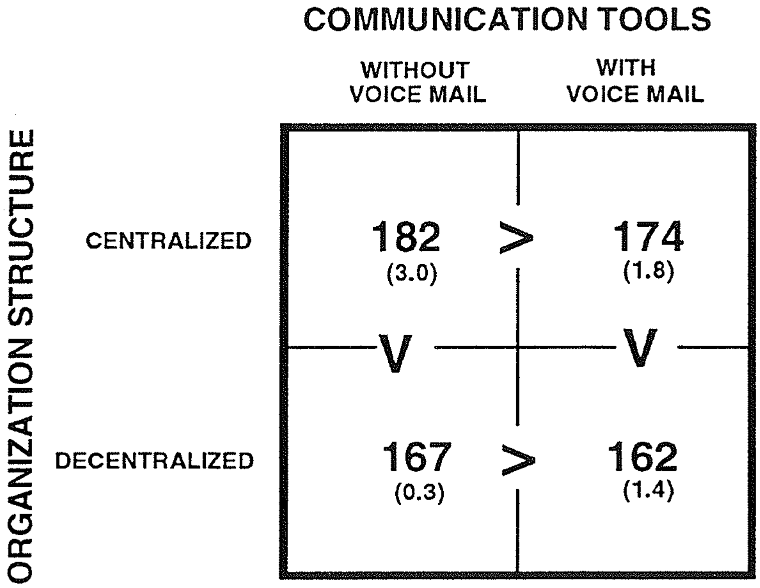

Figure 4. Effect of Communication Tools and Organization Stucture on Duration. VDT contingent predictions of change in project duration match qualitatively the predictions based on Galbraith's theory. Numbers in each cell show the mean and standard deviation (in parentheses) of project duration in working days for 3 simulation runs. The ">" indicates the qualitative prediction of the Galbraith (1977) theory, e.g., that the mean project duration of a centralized project without voice mail will exceed that of a decentralized organization without voice mail.

Despite the large number of intermediate variables that the VDT simulation determines stochastically, the standard deviations for three runs of each of the four experiments are all relatively small (less than two percent of the means), suggesting that the VDT simulation model is well behaved for this size project.

4.3. Modeling centralization and formalization policy

The second test case, the Table Mountain Project, was an electrical substation extension project that involved design, procurement and construction of a set of mechanically switched shunt capacitors at an existing facility (Christiansen, 1993). The project had a scheduled project duration of 18 months and an authorized cost of about 12 million dollars. The engineering design team consisted of about 17 engineers (including the project manager) over most of the 18 month project duration. We represented the functionally oriented organization as a *weak matrix* structure.

Figure 5 shows three way predictions of how changing level of centralization of control in organizations will affect project duration. The expected behavior from contingency theory is based on the assumption that higher level managers will make more rework decisions than low-level designers, because they have a more global view of different parts of the project. Thus, centralization will lead (stochastically) to more rework, and hence a longer project duration. The results of simulation are qualitatively consistent with the predictions of this theory and of the project manager. As shown in Figure 5 for the electrical substation project, the simulation prediction (a total increase in duration of 4% between lower and higher centralization) and the project manager's predictions (total increase of 8%) are in the same direction and order of magnitude.

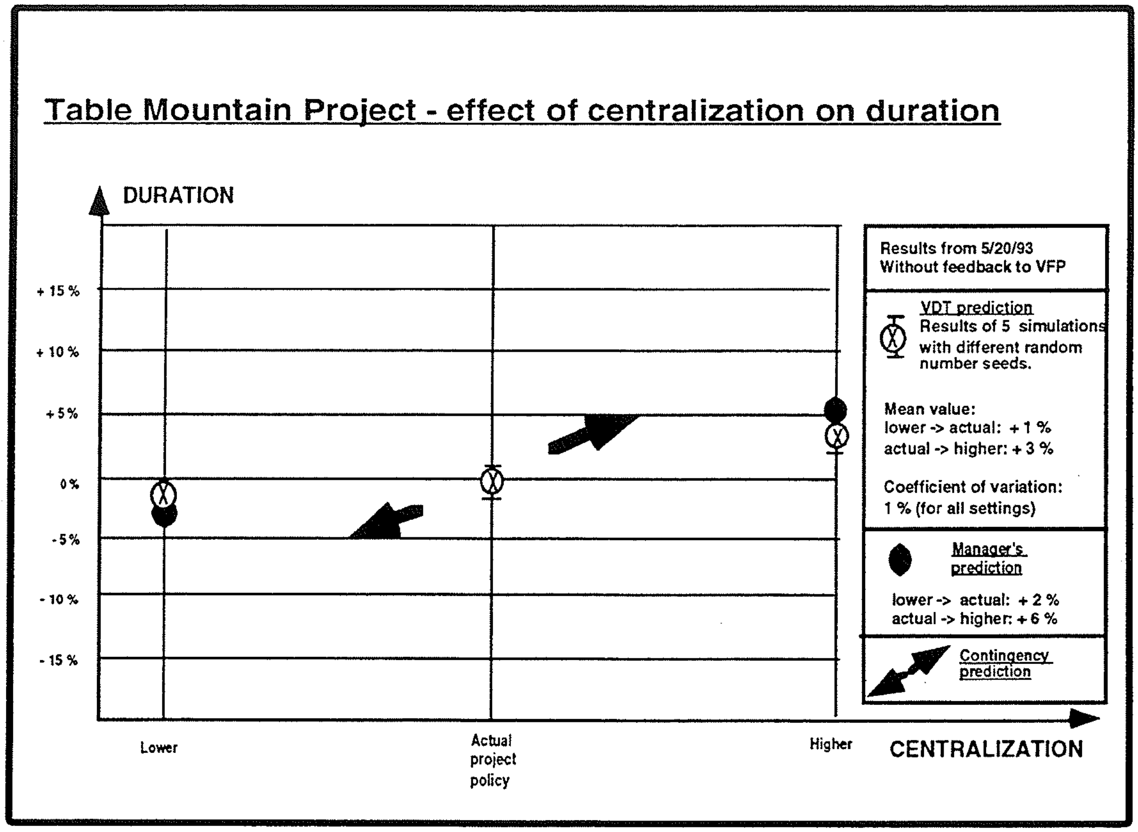

Figure 5 Impact of changing centralization on project duration. There is three-way qualitative consistency in the predictions of contingency theory, project managers, and the VDT simulation model.

Figure 6 shows VDT simulation results for the effect of changing centralization on the number of uncorrected non-conformances (the numerator of the verification quality ratio), together with the prediction from the project manager and the qualitative prediction from contingency theory. In this case, the theoretical assumption that managers have a more global overview leads to a prediction of fewer uncorrected non-conformances for higher centralization and more uncorrected non-conformances (when rework decisions are made by subteams) for lower centralization.

As shown in Figure 6, the agreement between the simulation results (a total decrease of 28% in uncorrected exceptions between lower and higher centralization) and the manager's prediction (a total decrease of 30%) is excellent for the Table Mountain electrical substation project. Similar results were obtained for the Statfjord project. In both of these tests, the coefficient of variation is larger than for cost and duration, but is still well below the predicted differences for different values of centralization.

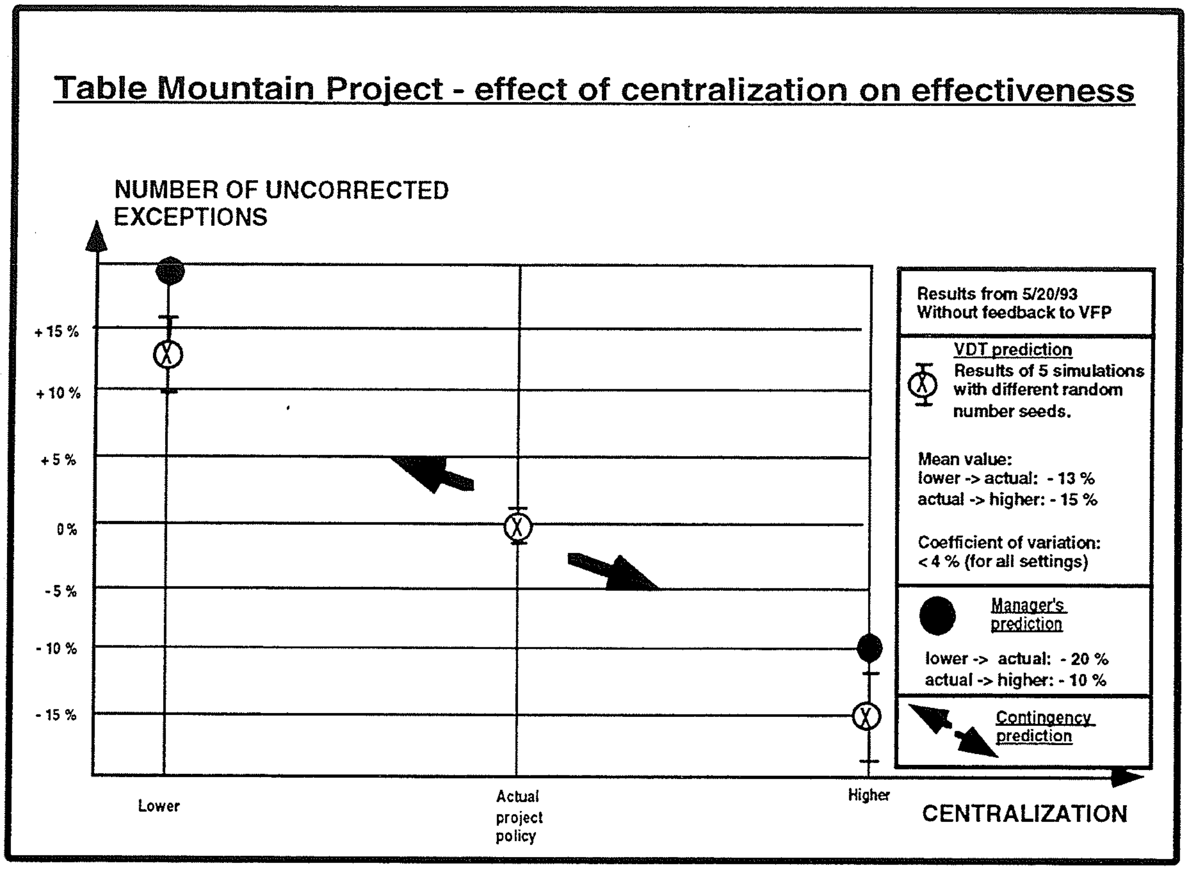

Figure 6 Effect of changing centralization on verification quality. As with predictions about duration, there is three-way qualitative consistency in the predictions of contingency theory, project managers, and the VDT simulation model.

4.4. Impact of formalization on project quality

Figure 7 shows predictions of the effects of changing formalization on communication quality. In the power substation extension project, the predicted behavior from contingency theory is based on the assumption that project teams within a functionally oriented organization need to formalize their communication policy. They will use formal, scheduled meetings to focus the team effort.

In this case, the project manager's prediction of the effects of changing formalization agrees with contingency theory. The manager's main reason for his prediction was the belief that more formal communication would prevent misunderstanding and confusion since the disciplines were not colocated and informal communication was relatively difficult. There is good quantitative agreement between the simulation prediction (a total decrease of 26% in number of non-attended communications between low and high formalization), and the project manager's prediction (total decrease of 22%). The coefficient of variation is well below the predicted difference in number of non-attended communications for different values of formalization.

In the Statfjord Project, the theoretical prediction is, however, opposite to that for the functionally oriented team in the previous example. Our theory predicts that the project team within this strong matrix organization will have higher effectiveness of their communication process with an informal communication policy that allows flexible coordination. Since project team participants are physically co-located and work on only one project, they can (and will) communicate informally and intensely to resolve the various interactions and interdependencies that arise from the large number of concurrent activities. This flexibility allows "fluid participation" (March 88) in communication. The effect of missing any given exchange is small, but the effect of missing many exchanges is detrimental. This theoretical prediction is consistent with the project manager's prediction, based on his belief that an excessively formal project policy sometimes caused inflexible communication patterns that were not always able to handle the intense coordination required between project team participants.

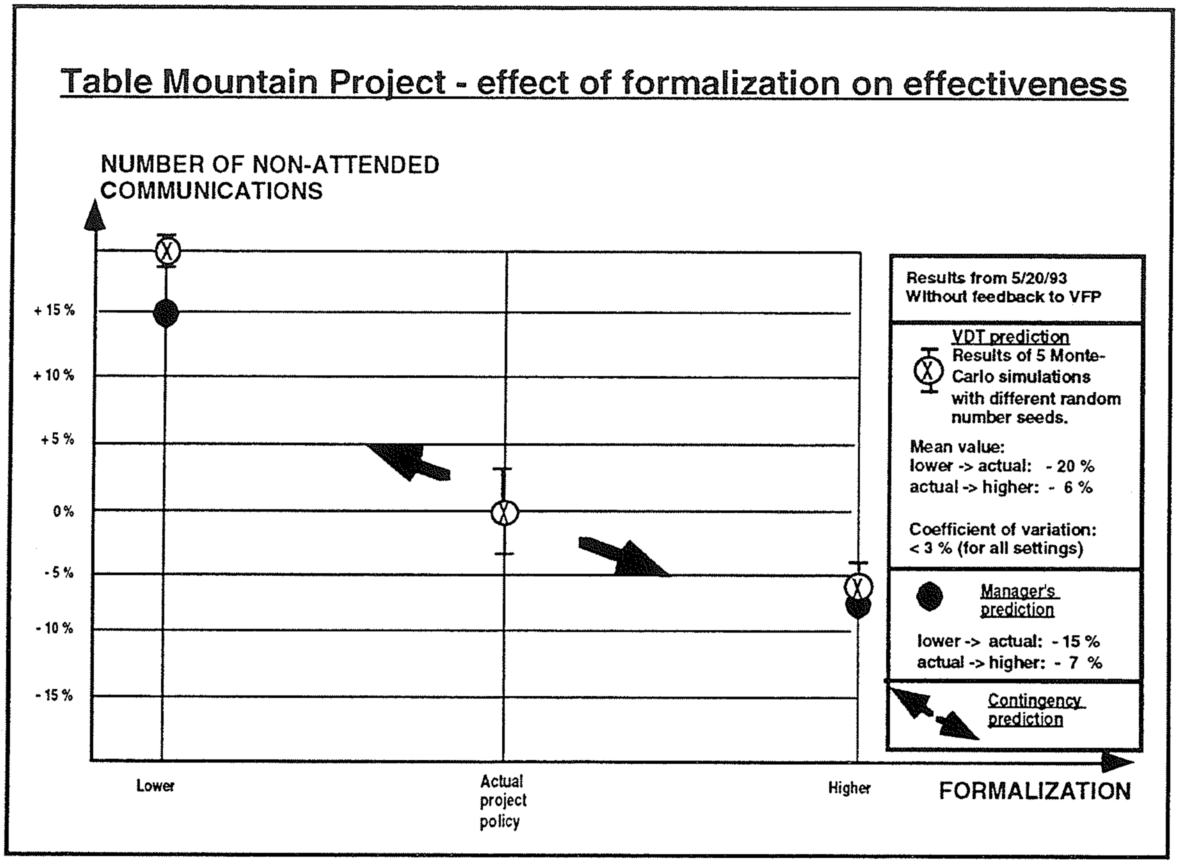

Figure 7. Impact of Changing Formalization on Communication Quality. The number of non-attended communications is an inverse measure of quality. The more communications that actors ignore, the worse the communication quality. As with predictions about duration, there is three-way qualitative consistency in the predictions of contingency theory, project managers, and the VDT simulation model.

5. Discussion

In summary, our experimental results show qualitative consistency among the predictions of theory, experienced project managers, and simulations. We claim that, for the types of complex but relatively routine projects that we have modeled, VDT produces aggregate performance predictions that are qualitatively reasonable. Calibration experiments to refine the values of internal variables in VDT are being conducted during 1994.

Besides these aggregate predictions which can be compared to predictions derived from managers or from contingency theory, VDT generates a wealth of data during each simulation run about the workloads and activities of individual actors. We have developed graphical visualization tools to facilitate inspection of these detailed performance data. For example, if centralization results in a longer project duration, it is possible, using VDT, to determine where bottlenecks are occurring. Thus, by inspecting actors' work history logs, we can determine which actors have spent excessive amounts of time waiting for decisions from supervisors. We can then inspect the depth of the in-trays of these actors' supervisors over the course of the project to determine which supervisors were overloaded with exceptions and were responsible for holding up decisions needed by their subordinates.

Once the key bottlenecks have been found, a user of VDT can propose decentralization of decision making, reassignment of subordinates to reduce the supervisor's span of control, better communication tools, or other changes in the structure of the design team's organization. Each proposed change can then be modeled in VDT and simulations conducted to see whether it produce a better overall result in terms of VDT's efficiency and effectiveness performance measures.

These kinds of predictions are not currently obtainable from organization theory; nor can managers easily predict where information overload will be concentrated in their organizations. Thus, we argue, VDT represents a prototype system which, when calibrated, will provide a unique capability for analyzing project organizations engaged in complex but routine work.

Accurate and reliable analysis tools will allow us to predict *a priori* the behavior of a proposed organizational configuration under a given set of requirements or "loads". Such tools can help to advance the organizational engineering process from its current trial and error adaptation mode to a more rational design process. We argue that reliable analysis tools, in turn, must be built on a foundation of operationalized, validated and calibrated theory. Extant contingency theory provides many of the important components of the required theoretical framework, and we believe that the extensions to it embodied in VDT represent a significant step toward a validated and calibrated organizational analysis tool for project teams.

6. Related Work

Cyert and March's (1963) pioneering simulation of department store and can manufacturing organizations provided early examples of the theoretical insights that could be gained from simulating organizational decision making in fine-grained detail.

The "Garbage Can" simulation model (Cohen *et al*, 1972) showed that a relatively simple simulation model could reproduce the kinds of outcomes observed in loosely coupled "organized anarchies"—organizations like universities, in which goals and means are both ambiguous and contested. The Garbage Can model captured aspects of organization structure including access structures of actors to choices and problems to choices. VDT's actor skills and roles build on these ideas from the Garbage Can model.

Burton and Obel's (1984) simple but elegant model of M-form *vs.* U-form organizations was more of a macro contingency theory model than VDT, but it provided important theoretical insights and continues to inspire us to simplify future versions of VDT through ongoing sensitivity testing of its various behavioral parameters.

Masuch and Lapotin's (1989) AAISS system demonstrated the use of non-numerical computing paradigms derived from artificial intelligence to model organizational decision making in clerical tasks and to predict the impact of various aspects of structure on performance. Carley and her colleagues (Carley *et al,* 1992) have extended the model of actors in AAISS to include learning and communication between actors. Like these systems, VDT uses AI-based non-numeric representation of attributes and reasoning, together with numerical computation of variables like durations. VDT's direct tasks are more abstract than in Carley's models; at the same time, its interdependence relationships and attention rules are more highly elaborated.

Computational organizational modeling has a parallel in the work of several computer scientists (Gasser 1991, Durfee et al 1989, and Shoham 1993). Distributed computation in massively parallel computers must face many of the same challenges as complex human organizations—i.e., the computing environment must divide a large task into tasks, distribute tasks for processing and then integrate results of distributed tasks into a coherent solution through information processing and communication.

We see object-oriented programming (OOP) languages as natural and intuitive conceptual frameworks for modeling organizations of human or electronic agents engaged in cooperative tasks. The non-numerical pattern matching capabilities of production rules that can be integrated in the OOP framework with tools such as the Kappa™ environment in which VDT was developed are particularly well suited for modeling organizations.

The widespread availablity of high level OOP tools has led to a resurgence of interest in computational modeling of organizations starting in the late 1980s. We believe that these new organizational modeling tools have the potential not only to contribute to the development of organization theory, but also to provide a conceptual bridge between organization theorists and computer scientists interested in distributed problem solving.

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