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Computational Enterprise Models:

Toward Analysis Tools for Designing Organizations*

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ABSTRACT: Engineers who design physical structures like bridges or buildings have long been supported by mathematical techniques, and more recently, by computational analysis techniques like the Finite Element Method. Engineers use these "virtual prototypes" during design, and perform "virtual experiments" to validate and refine new structural systems and even new theories of structural mechanics. The goal of the Virtual Design Team (VDT) research program conducted by the authors and their colleagues at Stanford University is to develop computational simulation tools that: (1) can be used by managers to generate and test alternative "virtual organizations" to systematize the practice of organizational (re)engineering, and (2) can be used by organizational researchers to perform "virtual experiments" to aid in validating and refining new theories describing the organizational dynamics of knowledge-intensive work. The second version of our simulation model, VDT-2—has been successfully validated by comparing its predictions with observations of multiple industrial design teams. VDT-2 thus provides significant new capabilities for analyzing the structure, policies and communication tools of project organizations engaged in complex, but routine, engineering tasks and for generating detailed performance predictions at the level of organizational "actors"—individuals or small, homogeneous sub-teams. This chapter explains the motivation for our initial focus on routine, project-oriented work and lays out a series of conceptual extensions that we believe will allow the framework to be used for modeling organizations at the enterprise level.

1. INTRODUCTION

Since 1989, the *Virtual Design Team* research group at Stanford has been conducting research to develop a theoretical framework and computational simulation model to predict the impact of changes in organization structure on the performance of project-oriented organizations engaged in knowledge work. The long range goal of this research program is to formalize theories and develop computational analysis tools that can support the systematic (re)engineering of organizations engaged in a variety of project-oriented and ongoing enterprises. The research was initially directed toward large and complex, but routine, design projects like design of power plants and oil refineries. For such design projects, both goals and means are clear and agreed upon by a majority of participants; coordination of large numbers of interdependent activities is the principal organizational issue to be addressed.

In this chapter, we argue for developing an enterprise level organizational simulation model through a series of stepwise extensions to the VDT-2 framework. The chapter discusses some abstractions we chose to make in the representation and reasoning of VDT-2, and presents a view of how its abstracted representation and reasoning capabilities can be extended in a number of ways to create a simulation tool for organizational (re)engineering, and for testing and refining theories about project-oriented enterprises engaged in less routine knowledge work.

1.1 The Need for New Enterprise Modeling Tools

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. Business Process Re-engineering is a time-consuming and costly undertaking that can pose significant risks to organizations engaged in making significant changes in their operations and structures. Thus, before implementing changes aimed at improving a process, managers would like to be able to predict the specific performance consequences of alternative task breakdowns, organization structures, and investments in information systems and communications technologies. Yet, organizational "contingency theory" [Thompson 67, Galbraith 77, Mintzberg 79] can provide only aggregated and qualitative predictions about how process or structural changes—which typically increase task interdependency—might affect organizational performance.

Modeling organizations engaged in project-oriented work should be relatively easy since projects, by definition, have well-defined goals and objectives, beginning and ending points, customers, and single point-of-accountability process managers. Yet project management tools such as the Critical Path Method have been shown to make consistently optimistic predictions about project durations. The "merge-event bias" inherent in deterministic network representation of tasks is one well-known reason for this optimism [Moder et al. 83]. The merge-event bias problem can be circumvented 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, existing project modeling tools tend to underestimate the impact of added coordination complexity on project duration.

Thus neither extant organization theory nor engineering management techniques can provide reliable and detailed predictions of organizational performance. We argue that there is a need for a new "micro-contingency theory of organizations," and for modeling tools based on this richer theoretical base, to answer questions about the effects on performance of changes in task requirements, actor capabilities, project organization structure and policy, and communication tools.

1.2 A Computational Organization and Process Modeling Approach

The development of social science and "social systems engineering" has been severely hampered by the lack of appropriate mathematical or computational analysis tools. Organizational theorists generally model the behaviors of interest to researchers or managers in terms of discrete, nominal or ordinal variables. Thus, there is a mismatch between their theories and the continuous, numerical mathematical tools that have served so well to model physical systems. During the 1980s, artificial intelligence researchers developed techniques for representing discrete, non-numerical variables and for reasoning about relationships among them [Clancey 89] [Kunz et al 89]. These non-numerical reasoning techniques provide researchers with a powerful new set of tools to begin developing rigorous computational models of problem domains using qualitative simulation with discrete, non-numerical variables.

The motivation for the VDT research program was the authors' belief that such qualitative simulation approaches could be employed to develop computational analysis tools for social systems. The *Virtual Design Team (VDT-2)* is a computer analysis tool for modeling large, multidisciplinary design organizations, consisting of human actors supported by increasingly sophisticated information processing and communication tools. Although others have proposed the use of computational models to simulate micro-organizational behavior [Cohen et al. 72, Bushnell et al. 88, Masuch and LaPotin 89, Carley et al. 90], the Virtual Design Team is a pioneering effort to employ ideas from artificial intelligence for modeling the aggregate behavior of full scale organizations engaged in realistic tasks —an approach that our colleague, James March, has termed "organizational wind tunnel research" [Cohen 92].

VDT models organizations as information-processing structures—a view of organizations that dates back to Max Weber's work in the early 1900s, and that is elaborated in the work of March, Simon, and Galbraith [March and Simon 58, Simon 73, Simon 76, Galbraith 77, March 88]. In this view—which seems especially applicable to organizations of "knowledge workers" such as engineers—an organization is an information-processing and communication system, structured to achieve a specific set of tasks, and comprised of boundedly rational information processing actors. Actors exchange information (termed "communications" in VDT) only along specified channels (e.g., formal lines of authority, informal structures) using communication tools with limited capacity (e.g., memos, voice mail, meetings, etc.). To represent these organizational entities, their attributes, relationships and constraints, VDT employs explicit descriptions of tasks, communications, actors, communication tools, and structure. A detailed description of VDT is beyond the scope of this paper and can be found in [Levitt et al. 94a]. We provide an overview in Section 2.

1.3 The Virtual Design Team as an Extensible Enterprise Modeling Platform

We believe that projects will become increasingly common as a way of organizing knowledge work. Authors like Savage [90] argue that knowledge workers of the 21st Century will be organized into "virtual networked teams"—temporary organizations with many of the characteristics of today's capital investment projects. Moreover, the most widely used current approaches to Business Process Re-engineering, e.g., [Hammer & Champy 93], can be viewed as attempts to transform ill-defined, ongoing work processes into a series of "mini-projects" each of which has a defined beginning and end point, a clear customer, its own suppliers (for whom the subject process is the customer), performance standards against which it can be measured, and a "process owner"—c.f. project manager—responsible for it.

The trend toward projects as organizing metaphors for knowledge work argues strongly for using an organization and work process modeling language like VDT that has been validated as a model of routine, project-oriented design work as a starting point for the development of work process models in other industries. However, some of the abstractions that made the initial domain so tractable—e.g., abstract task content, motivated actors, static structures—need to be re-evaluated in the context of potentially greater uncertainty in both goals and means of work processes, and longer time spans of the modeled work processes. In other domains, these abstractions that served so well in modeling routine design reliably and parsimoniously can then be enriched or extended as needed to address the modeling requirements of less routine work.

In the following, we provide an overview of VDT framework, discuss the most important abstractions in the representation and reasoning of VDT that currently limit its applicability to routine, project-oriented enterprises, and discuss planned or completed efforts to implement and test extensions to this framework on a wider range of work processes and organizations.

2. AN OVERVIEW OF THE VIRTUAL DESIGN TEAM SYSTEM (VDT-2)

VDT-2 explicitly incorporates information processing and communication models from organization theory that allow qualitative predictions of organizational performance. The inputs to VDT-2 are: a description of the design task, including project policy, the subtasks called activities that comprise it, and sequential dependencies among the activities; a description of the actors in the design team and of their organizational structure; and a listing of the communication tools (e.g., facsimile, voice mail, electronic mail, meetings) available to actors. VDT's behavior has been validated extensively for internal consistency. Its behavior also compares well with theoretical predictions about, and the observed behavior of concurrent design teams in several facility engineering domains. This work provides initial evidence that symbolic computer modeling can be used to express and test social science theories applied to real world organizations and the communication tools that they employ.

The simulation model can thus serve as a facility to formulate and test specific conjectures regarding the qualitative effects on project cost and duration of changes in the organization structure of the team, or in the communications tools available to participants. VDT can simulate changes in different aspects of project team performance, given changes in organization structure, communication tool availability and project policy, such as decision making centralization and formalization of communication. The implementation of VDT is based on discrete event simulation of the design process for a given set of product requirements. Given a description of the product to be designed, the design team organization, and the design process, the simulation produces predictions of the efficiency and effectiveness of the design process through explicitly simulating design actions of and interactions among design actors.

VDT calculates organizational efficiency and effectiveness as aspects of the performance of design teams. Measures of efficiency include the simulated critical path duration and the sum of all activity durations (a surrogate for design labor cost). Measures of effectiveness are obtained from considering how coordination items are dealt with during project execution. Coordination activity includes *communication* and *verification* tasks, and thus design process effectiveness is measured by the relative number of uncorrected exceptions (the verification quality) and the relative number of non-attended communications (the communication quality).

2.1 Organizational Concepts of VDT

The basic premise of the VDT model is that organizations are fundamentally information-processing structures [Galbraith 77]. To operationalize the information processing model, VDT employs explicit descriptions of *tasks*, *communications, actors, tools,* and *structures.*

Task: Our goal is to analyze engineering design teams carrying out routine designs. We, therefore, view the task of a design team as the completion of a set of pre-determined activities, e.g., design, review, and approve a series of components or sub-systems of the artifact to be designed. Each activity has a specified magnitude, skill requirements, and both precedence and functional interdependence relationships with other activities. To complete the activity, the responsible actor must process an amount of information defined as the magnitude of the activity, communicate with interdependent design team participants and resolve "exceptions" that arise in completing the activity. Activities are characterized by their complexity and uncertainty. The more complex and uncertain an activity, the more likely exceptions (such as failures) may occur during task processing.

Communication: A communication in VDT is an elementary packet of information sent from one actor through a specified channel to another actor, using a single communication tool. Communications can be information exchange, exceptions, decisions and noise. Completion of each activity involves processing the number of "design communications" specified by the activity's magnitude. Each communication has attributes of: time stamp, author, recipient, work volume, distribution list, ranking of natural idioms, variability of the associated task, and priority.

Actors: Actors include managers and design subteams from various disciplines, such as electrical, process, and mechanical engineering. The actor description includes role characteristics, such as position in the team hierarchy; authority for design, approval and coordination tasks; and allowed communication patterns (either strictly hierarchical or allowing peer-to-peer contact). The actor description also includes individual attributes, such as craft and skill (e.g., high skill in mechanical engineering); task experience (high, medium or low) and the natural idioms of communications that the actor processes most effectively (e.g., words, schematics, plans). VDT explicitly simulates actors' *attention allocation*, *information processing* and *communication* behavior.

Communication Tools: Each communication is transmitted via a tool selected by an actor. The VDT framework represents each tool in terms of values on a set of variables that are theorized to affect both the choice of tool and the results of that choice. The adoption and behavior of tools is then defined in terms of the relationships among the tool variables and the characteristics of the task, actors and organizational structure. Tools are characterized in VDT by their: 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 (volume 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., spoken words, text, schematics, geometry).

Organization Structure: Structure in VDT is defined by a set of organizational relationships among actors, and levels of authority of actors in specific roles. Organizational relationships among actors delimit the channels along which tools can be used to send communications. Relationships modeled in VDT include: *supervised-by* to implement hierarchical structure; *coordinates-with* to implement lateral relations among interdependent actors; and *socializes-with* to implement informal structure. A set of project-specific coordination policies assigns decision-making authority to actors in particular roles (e.g., *design manager*) for reviews and approvals. A centralized structure is implemented by policies that require these exceptions to be resolved by high level managers (e.g., the *design manager*); decentralized structures vest this authority in lower level managers (e.g., the *sub-team managers*).

2.2 Simulation Environment

VDT operationalizes Galbraith's information processing model of organizations by explicitly incorporating specific tasks and actors with attention allocation capabilities, and by simulating coordination issues at the micro-level in terms of explicit interaction among team participants. The VDT simulation environment reasons about the objects discussed in Section 2.1 above, and the organizational processes that facilitate coordination among team participants. The model is formal in that it includes the basic concepts of, and predicts behavior based on, a set of widely accepted theories. VDT is implemented on a Sun Microsystems Sparcstation using Kappa, an object-oriented programming environment from IntelliCorp, and the SIMLIB, a discrete event simulation system we developed on top of Kappa.

3. ENTERPRISE MODELING FOR RE-ENGINEERING

A typical enterprise is composed of multiple business, management and production sectors which reside in the same or different locations. In *Structure in Fives* [Mintzberg 83], Mintzberg presents a flexible conceptual framework for thinking about enterprises. He classifies organizational forms into five generic types each containing five generic components in different configurations. The five basic components of an organization include (1) Strategic Apex, (2) Middle Line, (3) Operating Core, (4) Technostructure, and (5) Support Staff. Mintzberg also discusses five coordination mechanisms for integrating the work of specialized units in an organization. This view of organizations synthesizes much of the contingency theory literature and provides the basis for current attempts to employ contingency theory findings for organization design such as [Burton & Obel 94].

Mintzberg's framework provides a high level framework for analyzing organizations through categorization and models how organization structure can impact performance through coordination mechanisms. However, his framework does not predict the effect on performance of low level changes in organization design, such as communication techniques, training, and organizational learning. Furthermore, contemporary organizations, driven by advanced technology and globalization, tend to be more network-oriented, and the boundaries between his five components become less visible. As a result, it becomes difficult and subjective to model contemporary enterprises in this way.

The goal of the **Process Handbook** research [Malone et al. 93] is to provide a set of theories, methodologies and tools, to enable the modeling and redesign of organizations in a more systematic way. The Process Handbook approach to enterprise engineering or re-engineering adopts a process-oriented perspective. It views processes as definitions and prescriptions of organizational activities and views systematic process design and innovation as a driving force to reach more efficient organizations. A key element of this work is a novel approach to representing processes, which uses ideas from computer science about inheritance, and ideas from coordination theory about managing dependencies.

The goals of this representation are to improve understanding of complex processes, to assist in the identification of process inefficiencies, and to facilitate generation and comparative evaluation of alternative processes. The Process Handbook thus provides a systematic methodology for synthesizing the design of processes and organizations; however, the analysis and evaluation of the process design are left to users.

The *Enterprise Modeling* research effort at the University of Toronto [Fox et al. 94] aims at (1) formalizing the knowledge found in Enterprise Engineering perspectives such as Time-based Competition, Quality Function deployment, etc.; (2) integrating the knowledge into a software tool that will support the enterprise engineering function by exploring alternative organization models spanning organization structure and behavior; and (3) providing a means for visualizing the enterprise from many of the perspectives described above [Fox et al 1994]. The TOVE enterprise ontology [Fox et al 1993] developed in this research provides a rich and precise representation of generic knowledge, such as, activities, processes, resources, time, and causality, and of more enterprise-oriented knowledge such as cost, quality and organization structure. Again, from the enterprise re-engineering point of view, this enterprise modeling research is focused on enterprise design rather than on providing an organization analysis tool to support the synthesis-analysis-evaluation cycle of organizational design.

By overlaying different kinds of project organizations onto the organization components of "Structure in Fives," as shown in Figure 1, we can see that there are different ways to integrate an existing enterprise into "project teams", including integration across hierarchical levels in the organization, integration across functions at a given level, and other combinations of the above. From contingency theory [Thompson 67, Galbraith 77] we understand that the effect of different groupings on enterprise performance depends on the nature of tasks, as well as on environmental (e.g., market) and technological (e.g., tools, methods, quality of actors) contexts. To achieve an effective and efficient enterprise organization, one must know how a given design of "project teams" will behave and be able to compare the performance outcomes of alternative designs. Our research on extending VDT to enterprise modeling attempts to respond to this need.

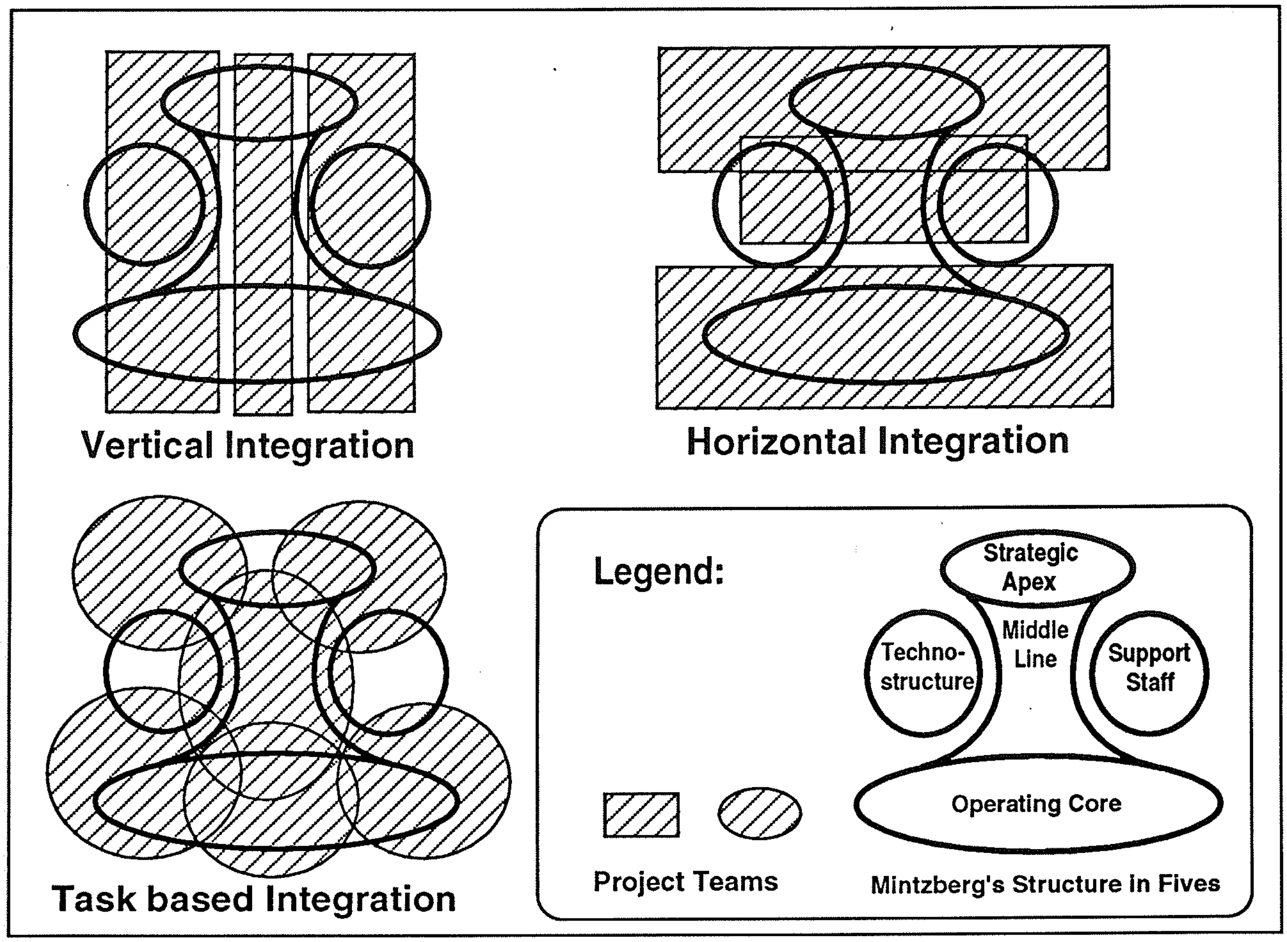

Figure 1: Enterprises as Collections of Projects—From Structure in Fives to Project-Oriented Enterprises (adapted from [Mintzberg 83])

As described above, modern organizations tend to be less hierarchical and their participants are more extensively networked. Thus, both information and control boundaries among traditional enterprise sectors become blurred. Tom Peters presents a series of case studies in which companies have adopted project organizations. He says, "Almost all of tomorrow's work will be done in project configurations. Functional staffs will all but disappear..." [Peters 92, p10]. Organizing dynamically for specific tasks will become a new trend for competitive enterprises.

Our *VDT* approach to enterprise modeling conceptualizes enterprise re-engineering as a process of transforming ill-defined, ongoing work processes into a series of "mini-projects" each of which has a defined beginning and end point, a clear customer, its own suppliers for which the process is the customer, performance standards against which it can be measured, and a "process owner" responsible for it. Based on this conceptualization, we are in the process of extending our VDT-2 framework, developed and validated for modeling single project organizations, into a model of project-oriented enterprises. The limitations of VDT-2 for this purpose and our ongoing and proposed conceptual extensions to address these limitations are presented in the next two sections.

4. LIMITATIONS OF VDT

VDT2 models an engineering design team in terms of tasks, communication, actors and organization structure. It simulates planned design activities and their implicit coordination requirements by assuming that: all activities and their assignment to actors can be pre-defined; actors are fully motivated; and organization structures are static. Although the assumptions have proved acceptable for modeling single design project teams, they cause significant limitations for VDT2 when applied to modeling enterprises.

Routine Tasks: The size and complexity of multiple project enterprises create significant uncertainties about the composition and assignment of tasks (or sub-projects). Interactions among multiple projects contribute further to their unpredictability. VDT-2 models "routine" design work for which activities are known in advance and are pre-assigned to appropriate actors. A great deal of work in enterprises is not routine by this definition. Modeling non-routine tasks requires both a richer ontology for task description to represent non-routine task situations, and a richer actor description [Jin & Levitt 93] to reason about the uncertain task situations, and to generate and assign tasks dynamically as the need for them arises.

Single Organization with Congruent Goals: VDT assumes that all actors belong to a single organization and are positively motivated toward achieving project objectives. It abstracts teams of 10 to 20 discipline-based specialists into compound, "subteam" actors which behave just like other actors except that they process information and exceptions at a rate which is a multiple of the single actor rate.

For enterprise modeling, multiple subteams whose members owe their primary allegiance to a variety of different parent organizations must work sequentially and in parallel on the same or different sub-projects. In this case, modeling organizations or even subteams as actors with congruent goals is clearly too abstract. Inter-organizational issues such as goal conflicts and competition for scarce resources along with devices to deal with these conflicts, such as contracts, incentives and development of trust between parties, must be explicitly addressed. To address this characteristic, we will need to explicitly represent economists' notions of agency, i.e., self-serving behavior and ways to regulate it, for both subteams and actors [Milgrom & Roberts 92].

Static Actor Attributes and Organization Structure: VDT2 models only static actors and organizations. VDT2 actors do not learn from their own experience or from others. As a result, organization structure and policies (e.g., centralization) remain the same throughout the simulation. Modern enterprises, however, must adapt themselves in order to compete in the changing world market and dynamic environment. Thus, for enterprise modeling, static assumptions about attributes of both actors and organizations are invalid. Actors (and consequently organizations) must adapt themselves through their own experience and their observation of others. To model this kind of dynamic organizational adaptation, VDT must explicitly represent and reason about internal and external performance feedback to actors and adaptation of goals, skills relationships and other parameters of organization structure [Oralkan et al. 94].

Simple Actor Behavior: As a result of routine task and single project team assumptions, VDT actors have rather simple, primarily statistical, behaviors. Because project activities and their assignment to team actors are pre-defined, actors in VDT2 do not need to reason about task situations to infer activity generation and assignment. VDT models exceptions and their resolution in routine projects using Monte Carlo simulation events for which frequency parameters on possible outcomes are set by qualitative inferences.

The static actor assumption, and the limited statistical decision making capabilities of VDT actors are bottlenecks to modeling non-routine tasks, where a variety of decisions must be made by actors in response to various task situations. The same limitations render VDT ineffective for modeling heterogeneous project teams, where agency issues among multiple actors and subteams can be critical to predicting overall enterprise performance.

Limited Representation of Decision Support Technology: Galbraith [77] describes organizations in terms of node capacity and communication channel capacity. In case of routine tasks, because decisions are mostly uniform, the impact of changing node decision-making capacity on team performance can be abstracted by changing actor processing speed. However, the impact of information technology on channel capacity and on the ability of actors to prioritize communications awaiting their attention remains important even for routine design work.

VDT was able to capture these impacts by modeling only the communications capabilities of tools like spreadsheets and 3-D CAD, not their decision support capabilities. However this limits its usefulness as an organizational analysis tool even in that domain, since it cannot address questions about how the decision support capabilities of proposed new tools might effect organizational performance, except as instantaneously accelerating the performance of work by each actor in isolation.

A richer model of work processes and of agent decision making implemented to address some of the limitations raised above should allow us to enrich our model to include, e.g., groupware tools, including the rate at which actors learn to use these tools, and the ways in which they can effect the quality of coordination through sharing of knowledge and information in an integrated decision-support mode.

5. FROM VDT-2 TO PROJECT-ORIENTED ENTERPRISE MODELS

Figure 2 shows how we are extending VDT's scope to meet the requirements of enterprise modeling. We start from the existing VDT-2, an organization model of a single engineering design team working on a single project. We then expand the scope of VDT-2 in two directions: from routine design tasks to non-routine production management tasks; and from single project to multiple concurrent projects. Finally, our experience with modeling non-routine tasks, and interactions between multiple projects and teams will allow us to address full scale enterprise modeling where multiple and different kinds of projects and teams are involved.

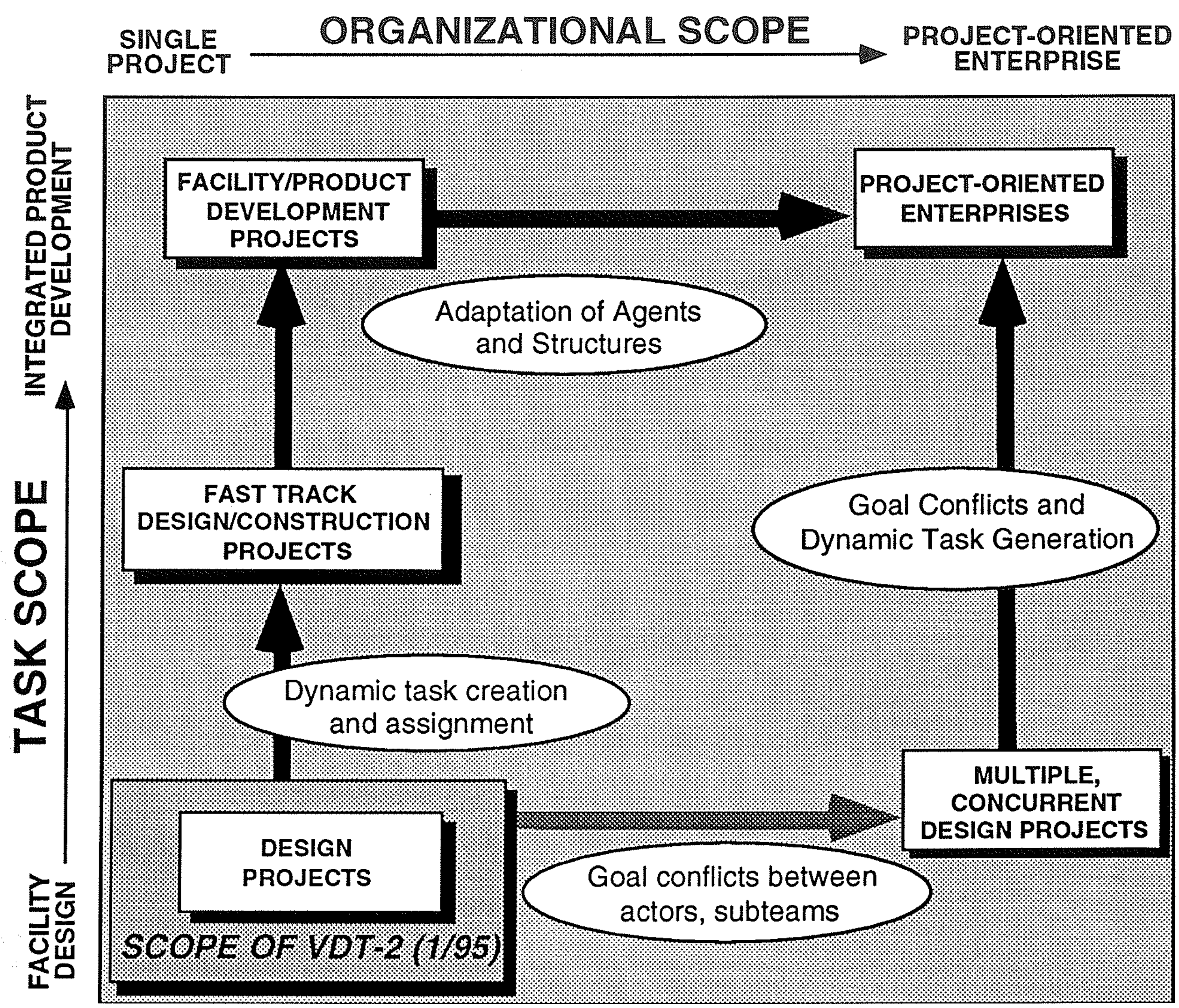

Figure 2 - From VDT-2 to Enterprise Modeling: How Proposed Extensions Will Enlarge VDT's Scope of Applicability

We have defined a set of research projects to pursue these extensions. We are, at present, in the process of extending VDT-2 to model non-routine tasks, multiple teams, and adaptive organizations. The remainder of this section describes the organization modeling issues that arise in making these extensions, and the agent-oriented approach we are employing to address these issues.

5.1 Modeling Specific Non-routine Projects

In our VDT research, we chose to focus initially on modeling organizations engaged in the design phase of complex but routine facilities like fossil power and petrochemical process plants. This strategy has been successful to date. The abstraction of task content and task-oriented actor behavior that could be assumed for the organizations engaged in such projects facilitated rapid development and testing of our initial modeling framework. To model enterprises, however, these abstractions are no longer valid, since tasks and actor behaviors for an enterprise can be highly unpredictable.

Enterprises usually involve multiple, and sometimes large scale, projects. The size and complexity of these projects create significant uncertainties about the specific activities that are required to complete them, and about their assignment to actors. Interactions among long term, non-routine activities contribute further to their unpredictability. Because of the unpredictability, it becomes impossible to directly pre-define all project activities and their interrelationships. For the reasons set out in Section 4, we believed that we could move VDT toward enterprise modeling by first addressing how to model work processes and actors in non-routine projects.

From an organization modeling point of view, the unpredictability or non-routineness of tasks may be reflected by complex exceptions, of the sort characterized by Galbraith [77]. During the execution of pre-planned tasks, exceptions may arise as a result of information uncertainty, environmental disturbance, or random errors of actors. In response to exceptions, pre-planned tasks may be modified or replaced; new activities may be introduced; and assignments of tasks to actors may be revised. In order to model such non-routine tasks, we first need information about what kinds of exceptions might arise in each task and environmental situation, and how actors might respond to each kind of possible exception, given their functional, organizational and social positions. Second, we need a framework or ontology to represent the context of exceptions and decisions made in response to the exceptions.

We have been developing a model of non-routine project work for construction projects—a class of projects that can be highly unpredictable. Based on our detailed analysis of work and exceptions in two kinds of construction projects—tunnel construction and building construction—we have achieved a better understanding of several kinds of generic exceptions that might arise during construction, and of the different ways construction managers choose to deal with different exceptions [Sugihara 94].

Based on this understanding, we have extended VDT's exception generation and decision-making process to model several different kinds of exceptions besides the "task failure" exception modeled in VDT--2. We have also modeled different kinds of decisions in response to exceptions. For example, a project manager may decide to add a new set of activities and assign them to certain team members based on rules about current work load, skill match, etc., when a serious exception has arisen.

To support this context-based exception-decision process, we have developed an extended process ontology which treats activities and exceptions as instances of a higher level class, and allows them to be instantiated dynamically by reasoning about context [Nasrallah 94]. Our enterprise task model will thus provide a rich framework to describe non-routine tasks. To make use of the framework in organization modeling, we will need a more sophisticated actor model that can reason about task situations and make decisions about what has to be done to resolve given kinds of exceptions in different task and environmental situation. Section 5.4 describes how our agent-oriented framework for enterprise modeling will address these requirements.

5.2 Modeling Multiple Projects and Teams

There are two basic issues involved in modeling multiple projects and teams. The first issue is how to model dependencies between activities in different projects explicitly; the second is how to model interactions among multiple team organizations explicitly. In our enterprise model, we will treat dependencies among activities that belong to different projects in a more sophisticated way than we do for activities in VDT-2 [Levitt et al 1994a].

Two modest extensions to VDT task model appear to provide much of the required functionality for modeling precedence relationships in enterprises. First, in addition to strict precedence relationships that exist in VDT-2, we will model a relationship we call "prerequisite" in which we can specify a minimum level of required completion for the prerequisite activity before the constrained activity can be started. Violating the minimum completion status of a prerequisite activity is possible, but only at the cost of a higher expected failure probability for the constrained activity. In addition, we will model dependencies between interdependent projects at the project level through aggregating activity dependencies.

For example, concurrency is one of the dependency measures we introduced to model project relationships. Assume we have two projects, project P1 and project P2. We can measure the concurrency of the two projects by the proportion of the total amount of work of one project that must be completed before the second project can start. This proportion of work can be calculated based on the pre-requisite relationships between the activities of the two projects.

As mentioned above, project-oriented enterprises tend to exploit networks of relationships between their participants, rather than trees as in simple one-dimensional hierarchies or even matrix organizations. Moreover, project teams may have members who belong to different parent organizations with different goals, and may work in diverse locations. The interactions, including control and communication, among such teams can thus depend in large part on the extent to which team members are able to develop shared goals for the project as well as mutual trust.

The extent of goal congruency was ignored in VDT-2 with its single organization, and task-oriented "engineering nerd" view of agents. From an enterprise design point of view, understanding the impact of agency and designing better agent control systems, such as reward systems, contracting systems, monitoring systems, and reporting systems, become critical for successful modeling and prediction. In our ongoing enterprise modeling research, we will explicitly represent agency of project teams and their members through introducing additional organizational attributes to represent different control systems, and through using sophisticated agent models that can possess different types of agency and respond appropriately to the control systems. At present, we are studying agency effects on project performance through observing a number of project-oriented enterprises. We will build our agency models based on these observations.

5.3 Modeling Adaptive Organizations / Teams

The final research issue we will discuss in modeling large enterprises is the adaptive nature of organizational action. To model ongoing enterprises, we will need to represent and reason about: (1) non-routine projects that can not be executed with predefined tasks and assignments, (2) multiple projects that make attention processes more complex, and (3) multiple teams that need to learn to interact given their differences in goals and culture, and (4) simulation time that spans over multiple projects for several cycles of organizational action. Organizational learning or adaptation becomes a key issue for realistic models in this domain. We view this as the most challenging research issue in the path of extending a static model like VDT toward reliable enterprise modeling. We will thus address it in greater detail than the previous issues discussed in this section.

In addition to the internal complexity of full scale enterprise organizations, there are two major reasons why modeling the learning organization is necessary. First, large enterprises face complex organizational environments that change over time. We are modeling multiple projects over long periods of time with multiple teams participating, and over long enough periods that changes occur in the environment. The interpretations of these changes by the teams involved, and the responses constructed by actors based on these interpretations, thus become more important. Teams and the enterprise learn from their past responses to the environment and the feedback they get from the environment, and they adapt their future interpretations and responses based on these past experiences in each new cycle of action.

There is also a second kind of organizational learning or adaptation that takes place in response to a top-down change in the organization. This could be a change in organizational structure, contractual structure between multiple participants in a project, a newly introduced technology, or a new task structure. These kinds of top-down changes embedded in existing structures have both intended and unintended consequences. Intended consequences (which are first-order and relatively easier to predict in the short term) may, in the long term, be mediated by the unintended consequences of top-down changes. The unintended consequences of a top-down change can be studied by modeling the organization as an adaptive system that operates within a structural context. The responses of individuals, teams, or enterprise organizations to these top-down changes provide the second application area for an adaptive organizational model.

Theoretical foundations of organizational learning. March and Olsen [76] describe experiential organizational learning as a cycle of stimulus-response pairs. Individual action is based on individual beliefs about self, the organization, and the environment. Individual action translates into organizational action through system interactions. The organizational action evokes an environmental response. The environmental response is evaluated and interpreted by the individual who in turn changes his/her beliefs. The modified beliefs influence future action creating a new cycle of learning. (Figure 3).

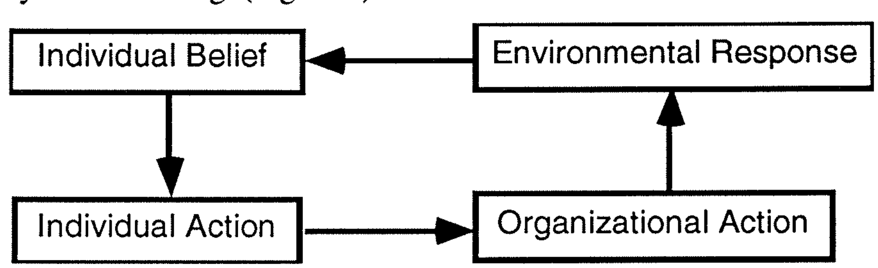

Figure 3 - Organizational Learning Cycle (adopted from March & Olsen 76)

This complete cycle of learning, although representative of the basic processes, is too idealistic and abstract for real-world situations. Organizational learning cycles are usually incomplete [Hedberg 81]; and March and Olsen [76] describe breakdowns in the stimulus-response relation in the cycle. When individual beliefs can not be applied to modify individual action, "role-constrained learning" takes place. When individual action does not get translated into organizational action, "audience learning" takes place. Also there are times when organizational action can not be mapped onto the relevant environmental response, leading to so-called "superstitious learning". Finally, individual beliefs may get erroneously modified due to the incorrect mapping of action to environmental response which creates "vicarious learning". These incomplete cycles are created or can be remedied to a certain extent by organizational structures, and culture. Thus, if one can map out the structural or contextual variables that mediate each stimulus-response (SR) relation in the cycle of organizational learning, and the nature of feedback from the learning cycle to the organizational context, a rich model of organizational learning can be constructed for analysis. Figure 4 is an initial attempt at mapping this terrain.

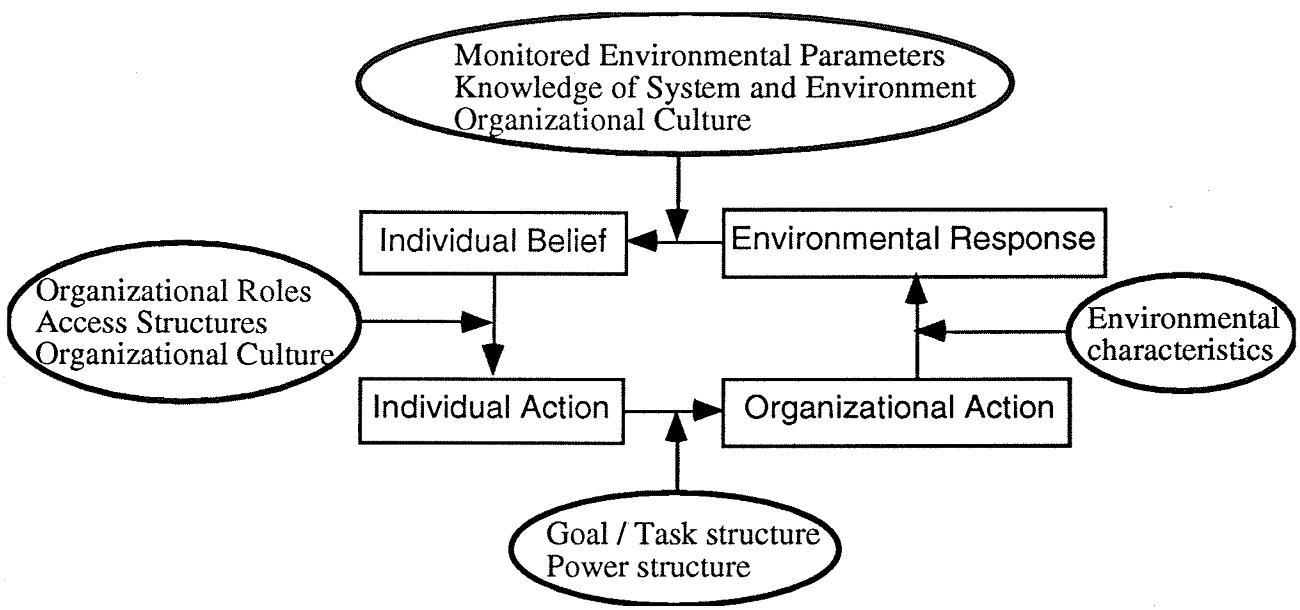

Figure 4 - Interaction of Organization Structure and Organizational Learning

This view of organizational learning fits naturally with the structuration view of organizations. "Structuration Theory" [Giddens 84][Sewell 92] treats structure as both the medium and outcome of organizational action; the organizing principle of Weick [79, 90], [Weick & Roberts 93] emphasizes structuring over structure, organizing over organization. Both reflect a dynamic view of the context within which action takes place. Context or conceptual structures constrain and facilitate action, but they get enacted, selected, and retained through action. The structure which is conceived of in various ways in each individual's beliefs gets enacted through individual action, and becomes observable as a systematic pattern, as individual action aggregates into organizational action. This dynamic is created by the concept of agency, the ability and power of agents to interpret conceptual structures, enact them, communicate with other agents, and monitor both their own and others' performance in order to modify their beliefs and actions. At the core of this view of agency lies adaptation, which enables system adaptation to emerge as the result of interactions among adaptive agents.

As implied by Figure 4, the context or organizational structure in which experiential learning takes place effects the nature of stimulus response mapping in the cycle of learning. Understanding and modeling the effects of context and structure become of increasing value when a top-down change is introduced into the organization. For example, the introduction of a new information technology both adds new structures and requires some direct modifications in existing organizational structures. Each technology embodies a set of rules and resources that are embedded in it at the time of technology development. These rules and resources are selectively interpreted, applied, reinforced, or discarded by the agents, as they interact with the technology and with others using the technology, just like other organizational rules and resources guiding agent action. As these structures get used, tested, selected, and some are retained while others are discarded, organizational change takes place.

Organizational change is not limited to the observable changes in patterns of interaction that reflect the structure of the system. Deeper changes occur in organizational knowledge, values, norms, and culture as well as agents' perception of and belief in these. Changes in these deeper structures get reflected in observable structures or patterns of interaction. Thus, adaptive organization models need to be able to reason about these deep structures and their effect on agent behavior.

The issues in modeling the effect of a top-down change (e.g., a new information technology) on an organization include:

(1) How are existing rules and resources in an organization matched up with the rules and resources imposed by this top-down change in guiding agent action;

(2) What specific agent actions are influenced by these interacting structures;

(3) How do agents choose to appropriate these rules and resources in their interactions, thus what structures are used, created, or modified; and

(4) What are the local and global performance implications of these structuration processes.

An adaptive organizations framework should attempt to answer these questions. If we can begin to answer these questions, we can start predicting what kind of organizational structures and associated forms would provide the best performance with, for example, each kind of information technology, given that long term, internal adaptation to a top-down change will take place along with short term adaptation by the agents most directly impacted with the change.

5.4 Our Proposed Agent-Oriented Modeling Approach

So far we have described a set of planned and ongoing extensions to VDT in the form of modeling (1) non-routine tasks with more detailed task content; (2) enterprises that work on multiple projects simultaneously; (3) intra or inter-organizational project teams that consist of sub-teams with multiple sub-cultures and goals; and (4) organizational adaptation to a changing environment or to a top-down organizational change. In order to support each of these extensions, there are two fundamental modeling issues that must be addressed. First, we need a richer ontology for task and task environment description so that non-routineness of tasks and interactions among tasks can be described. Second, we need a sophisticated actor model that can reason about task situations, infer the needs for task generation and assignment, learn, and carry out appropriate actions to satisfy these needs. As described above, our ongoing work on modeling construction projects has made a significant extension to VDT task ontology to cover the context-based exception and decision process—one important feature of non-routineness of engineering projects [Nasrallah 95]. In this subsection, we provide an overview of our agent-oriented approach to modeling more sophisticated actors.

We are developing a framework, called *O-Agents,* to model organizational agents based on *i-Agents,* an agent-oriented framework developed in our previous research on intelligent agents [Jin and Levitt 93]. An important difference between an o-Agent and an i-Agent is that while an i-Agent is designed to solve problems, including coordination problems, in the most effective and efficient way possible, an o-Agent is designed to mimic human behavior at abstraction levels which may sometimes be ineffective or inefficient. Despite the differences in agent rationality implicit in the goals of these two systems, we have found that the architecture of i-Agents is sufficient to model O-Agents. Thus, O-Agents will employ the basic i-Agents architecture but will change the knowledge or "character" of its agents to make them organizational.

In O-Agents, an agent has two types of attributes; those that describe its "character" which is modified over time through learning; and those that describe its current mental state which represent its view of task and organization situations and may change dynamically as the situation changes. In terms of "character" there are three attributes that we consider for our enterprise modeling framework: (1) Capabilities (i.e., competencies) (2) Values (i.e., motivations) ; and (3) Strategy. "Capability" of an agent refers to the area(s) of expertise held by the agent. It should match the level of detail in our task requirements, and should be comparable to the capabilities that are provided by technologies with which agents cooperate. Capabilities are not static in an adaptive organization, agents may expand their expertise by working with other agents, and by using technologies such as expert systems. The capabilities attributed to an agent are connected to a set of knowledge sources which are applied by the agent to reason about task situations and to infer needs for task generation, task assignment, and several kinds of learning.

"Values", which are represented as a set of criterion in O-Agents, define what the agent considers important at an abstract level, and guide most choices of agent action. Agents may value, for example, efficiency, power, personal competence, autonomy, or cooperation. Ranking of values changes from agent to agent, but is greatly influenced by the culture of an organization that chooses individuals with values consistent with its organizational culture and rewards them for maintaining appropriate values over time. By modeling different values for different groups of agents we can start addressing issues like the effect of socialization, incentive structures, culture, and hierarchy on creating cooperation or conflict in multiple team situations.

The "strategy" attribute refers to the tactics agents use in interacting with other agents, and in adapting to the organizational environment. Strategies are guided by values. Agents may have strategies about communication with other agents, or selection of tasks and technologies. We use the strategy attribute, together with the values attribute, to model agents' (economic) agency and coordination behavior. For example, agents may have a strategy of responding to supervisors in a timely fashion, but delaying their responses to peers' and subordinates' communications. From a learning perspective, values and strategies adapt to agent's experience. From a structuration point of view both values and strategies are constrained by existing organizational structures, and are used in turn to re-shape these structures.

In terms of "mental state", agents have capacities, commitments, beliefs, and knowledge about others that change over time. "Capacity" of an agent refers to the resource constraints (i.e., time, tool) an agent is facing at a given point in time to perform his/her task although he or she is normally capable of doing that task given the resources. "Commitment" is what the agent has volunteered or been assigned to do within a given time period. This could be a task with a time deadline. Commitments become more problematic when task structures are not predefined but are created in real-time. In this situation, commitments to allocate one's capacity (e.g., among multiple projects) are greatly influenced by one's beliefs about the world.

"Beliefs" are agent's view of the world (e.g., status of the multiple projects). Beliefs may be shaped differently depending on the amount of information agents can get about the world and on their values and capabilities. This difference complicate the organization's behavior by introducing conflicts among agents. Rational agents make their decisions (e.g., to select a strategy for action) through reasoning about the current state of the world, including task and organization situations, and the potential effects of applying various action strategies in the current situation to achieve outcomes consistent with their goals. Boundedly rational agents in O-Agents, however, have limited access to information and limited time to examine the consequences of a decision. Through restricting agents' view of the world and limiting the kinds of knowledge attached to agents, we can model different kinds of boundedly rational agents found in enterprise organizations.

As described above, agents' knowledge about task processing and coordination is attached to "Capabilities" and "Strategies", respectively. Another type of knowledge—knowledge about other agents—is represented as part of agents' beliefs. Non-routine tasks and learning project teams involve extensive interactions among agents, such as task assignment, information exchange, learning from others' experience, etc. Agents' knowledge about others is a key factor that affect the interactions. Through varying the level of knowledge about others for different agents in a given enterprise setting, we can model different organizational situations in which we can study the effect of different incentive systems, task generation policies, and organization structures.

A major issue in setting micro-level agent attributes is that of distribution. An intra-departmental project team may have a relatively homogenous population of agents; whereas a project team that crosses hierarchical levels, and departmental or even organizational boundaries will have a much more heterogeneous agent population. The amount and kind of heterogeneity (i.e., conflicting vs complementary) will create interesting results in terms of adaptation, cooperation and overall performance of the project.

O-Agents is being developed based on lessons learned from both VDT and i-Agents research. The success of VDT applications in modeling routine project teams and of i-Agents applications to modeling distributed construction planning has led us to develop O-Agents. We believe that inserting the more sophisticated O-Agents into VDT's task, actor and structure framework will provide VDT with significantly enhanced potential and flexibility for modeling project-oriented enterprises.

6. RECAPITULATION

In a previous book chapter on computational organizational modeling [Levitt-et-al-94b] we described our VDT framework for modeling project organizations engaged in complex but routine design work. Since then, VDT has been refined, tested and validated against more than ten real world projects. VDT has been found to make predictions that agree both with the aggregate predictions of the underlying theory and with the specific predictions of experienced project managers.

This chapter has set out our evolving view of the challenges in extending VDT toward a framework that will ultimately provide the same kind of reliable "organizational wind tunnel" for organizational engineers and scientists to analyze the performance of enterprise organizations. We have argued that enterprises engaged in knowledge work are rapidly adopting project organizational forms, so that the VDT framework, which combines qualitative inference with Monte Carlo simulation to model abstract tasks and actors involved in routine project work, represents a reasonable starting point for developing an enterprise modeling framework. At the same time, we have tried to show that VDT's current framework has several inherent limitations as a model of less routine work in long lived enterprises.

Through a discussion of these limitations in the VDT framework and the issues involved in overcoming them, we have attempted to make a case for using: an expanded ontology of tasks, actors and structure to represent non-routine work; and a rich, agent-oriented model of actor behavior to model adaptive enterprises engaged in a variety of project-oriented work.

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