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The Virtual Design Team (VDT): A Multi-Agent Analysis Framework for Designing Project Organizations[1]

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Abstract— *The Virtual Design Team (VDT) is a multi-agent modeling and simulation framework that has been developed over the past 15 years to help project managers design work processes and organizations for highly concurrent, "fast-track" project work. VDT has been extensively validated as an analysis tool for project organizations engaged in a routine—albeit complex and fast-track—product development efforts. Three important limitations of VDT are (1) it models only routine projects for which all tasks, agents, and relationships between and among them can be prespecified and held constant; (2) it assumes that all exceptions are handled hierarchically; and (3) it ignores any goal incongruency among project participants. This paper describes VDT, highlights its limitations, and presents ongoing research that is attempting to address these limitations.*

1. INTRODUCTION

The Virtual Design Team (VDT) is a multi-agent modeling and simulation framework that has been developed over the past 15 years to help project managers design work processes and organizations for highly concurrent, "fast-track" project work [1], [2]. VDT operationalizes, extends and quantifies Jay Galbraith's information processing view of organizations [3]. Boundedly rational agents process chunks of information associated with: (1) performance of their assigned tasks; (2) supervision of other agents; (3) coordination with agents responsible for interdependent tasks; and (4) rework resulting from errors or changes that arise in their own tasks or in other agents' interdependent tasks.

Evidence from multiple fast-track product development efforts has shown that the primary cause of failure for these knowledge intensive dynamic systems is exactly this kind of backlog-induced organizational breakdown resulting from a combination of direct work and "hidden work"—the workload associated with supervision, coordination and rework. Experience indicates that interdependent tasks can be overlapped up to a certain point, with a roughly linear increase in workload, after which hidden work increases exponentially and eventually overwhelms the organization's information processing capacity.

The research to conceive and build VDT began with ethnographic studies to quantify the magnitude of supervision, coordination and rework tasks for typical product development efforts. We then designed and built VDT as a multi-agent system made up of simple information processing agents characterized by skill sets and experience, organized into project teams, and assigned to tasks with sequential interdependence, technical interdependence, and failure or rework interdependence. VDT agents were given rules for attention allocation, exception referral, decision-making about exceptions, and communication.

VDT has now been validated and calibrated to generate quantitative predictions of backlogs, delay and quality risks in fast-track projects. This paper explains the original multi-agent "information flow physics" model of work embodied in VDT, and describes past, ongoing and planned future extensions to the framework to address these and other limitations of VDT as an analysis tool for designing organizations of multiple human and computer agents in 21st century organizations.

2. VDT REPRESENTATION AND REASONING

This section explains the VDT model representation and reasoning. (Additional details of VDT's representation and reasoning are provided in [4].)

The VDT modeling environment was developed by operationalizing and quantifying Jay Galbraith's information processing view of organizations [3]. Following Galbraith, agents derive their total workload from direct work, exception handling and coordination tasks. Depending on the match between an agent's skill set vs. the skill requirements, complexity and uncertainty of its assigned tasks, the agent will encounter more or fewer exceptions in

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processing its task. As the degree of interdependence between tasks increases, any exceptions that arise will tend to propagate more widely and create additional information processing load for the agents assigned to interdependent tasks. As the span of control (i.e., the average number of subordinates reporting to each agent) increases, the amount of information processing associated with supervisory exception handling by managerial agents will increase.

For a given work process, organization structure and task assignments, some of the boundedly rational agents in the organization may become excessively backlogged. As agents become backlogged from a combination of direct work, supervisory work, coordination work and rework, they tend to focus on their own assigned tasks, and tend to underemphasize supervision and coordination with other agents. Agents that are not receiving adequate supervision tend to make poor decisions that increase their downstream error rates, and ultimately compromise quality for their task outputs. When interdependent agents become too backlogged to coordinate adequately with one another, the likelihood of incompatibility between their interdependent task outputs increases, degrading the system-level quality of the team's work products. Thus, backlogs not only trigger risks of schedule delays, but also increase component and system level quality risks [5].

This information processing view of organizations has two key implications. The first is ontological: we model knowledge work through interactions of *tasks* to be performed, *agents* communicating with one another and performing tasks, and an *organization structure* that defines agents' roles and constrains their behaviors. Figure 1 illustrates this view of tasks, agents and organization structure. As suggested by the figure, we model the organization structure as a network of reporting relations, which can capture micro-behaviors such as managerial attention, span of control and empowerment, and we represent the task structure as a separate network of tasks, which can capture organizational attributes such as expected duration, complexity and required skills. Within the organization structure, we further model various *functional roles* (e.g., marketing analyst, design engineer), which can capture organizational attributes such as skills possessed, level of experience and task familiarity and *project roles* (subteam, subteam leader or project manager), which affect decision making micro-behaviors such as likelihood of performing rework when faced with exceptions. Within the task structure, we further model various sequencing constraints, interdependencies and quality/rework loops, which can capture considerable variety in terms of how knowledge work is organized and performed.

As also suggested by the figure, each agent within the intertwined organization and task structures has a queue of information tasks to be performed in its in tray (e.g., direct work tasks, meetings to attend) and a queue of information outputs (e.g., assigned work tasks, messages from other agents, completed work products, communications to other agents, requests for assistance). Each agent also processes such tasks according to how well the agent's skill set matches the skill required for a given task, the relative priority of the task, the agent's work backlog (i.e., queue length), and how many interruptions divert the agent's attention from the task at hand. Agents' collective task performance is further constrained by the level of effort that agents allocate to each task, the magnitude of the task, and both scheduled (e.g., work breaks, ends of shifts, weekends and holidays) and unscheduled (e.g., awaiting managerial decisions, awaiting work or information inputs from others, performing rework) downtime.

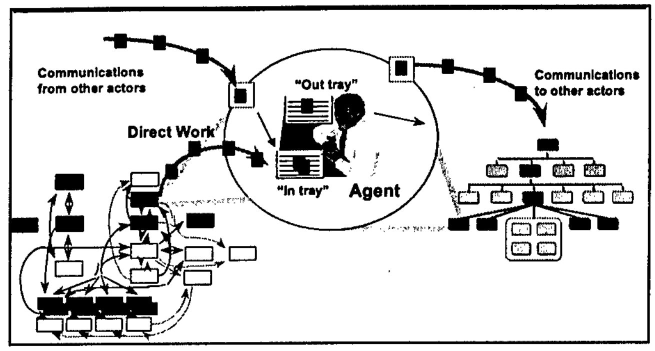

Figure 1 - VDT Information Processing Model

The second implication is computational: Both primary work (e.g., planning, design, management) and coordination work (e.g., group tasks, meetings, joint problem solving) are modeled in terms of *work volume* (i.e., person-hours or person-days). This construct is used to represent a unit of work (e.g., associated with a task, a meeting, a communication) within the task structure. In addition to symbolic execution of VDT models (e.g., qualitatively assessing skill mismatches, task-concurrency difficulties, decentralization effects) through micro-behaviors derived from organization theory, the discrete-event simulation engine enables (virtual) process performance to be assessed (e.g., quantitatively predicting task duration, cost, rework, process quality).

Clearly quantitative simulation places additional burden on the model developer in terms of validating the representation of a knowledge-work process. This generally requires fieldwork to study organizations in action. The VDT modeling environment benefits from extensive fieldwork in many diverse enterprise domains (e.g., power plant construction and offshore drilling [5], aerospace [6], software development [7], healthcare [8], [9], and others). And through the process of "backcasting"—predicting known organizational outcomes using only information that was available at the beginning of a project—VDT models of real enterprises have demonstrated dozens of times that simulated organizational behaviors and results correspond qualitatively and quantitatively to their actual counterparts in the field [10], [11].

Viewing VDT as a validated model of project-oriented knowledge work, researchers have begun to use this dynamic modeling environment as a "virtual organizational test bench" to explore a variety of organizational questions, such as effects of distance on performance [12] or to replicate classical empirical findings [13]. Thus, the VDT modeling environment has been repeatedly and longitudinally validated as representative of both organization theory and enterprises in practice. This gives us considerable confidence in its results.

After about three years of calibration, VDT began to make startlingly accurate predictions of project durations, and of the loci of quality breakdowns, for multiple fast-track construction and aerospace projects. An early version of the software was commercialized as SimVision® and is currently being used by multiple fortune 100 companies to diagnose and mitigate schedule and quality risks for projects in the petrochemical and energy sectors [14].

3. Limitations of VDT

The original version of VDT and its SimVision derivative have three significant limitations. We describe these next.

First, VDT is only applicable to relatively routine—albeit complex and fast-track—product development efforts. The modeling assumptions require a fixed sequence of tasks, a fixed organization structure and fixed task assignments. Any required rework simply adds work volume to the original tasks performed by the originally assigned agents. For the kinds of service and maintenance work that are growing in importance in the 21st century economy, diagnosis tasks trigger one of many possible repair strategies. Side effects that emerge in treating identified problems must, in turn, be diagnosed and treated -- often by additional specialists who were not included in the original organization -- in order to complete the original task. A more dynamic representation of both work processes and organizations is required to model and simulate this kind of less routine work.

A second limitation of VDT is that it assumes all exceptions are handled hierarchically. This "boss knows better" model of knowledge work fits 20th-century work in relatively slowly evolving technologies. However, for many 21st century projects involving software development, biotechnology and other fast-changing technologies, supervisors have been trained in earlier and now obsolete technologies. For example a Java programmer might report to a boss who was trained in C++, and whose boss was trained in Fortran; or a microbiologist might report to a supervisor trained in cell biology whose boss was trained in plant or animal biology. The real experts who can help to resolve technical exceptions tend to be highly educated and experienced peers residing in other projects, or even other companies. Knowledge workers develop and maintain knowledge networks that connect them to a variety of distributed knowledge sources that they exploit to resolve exceptions. Integrating VDT's workflow model with models of the evolution and operation of knowledge networks such as Blanche [15] provides a way to model and simulate this kind of network-based exception handling.

A third significant limitation of VDT is that it assumes agents have congruent goals, values and behaviors, so that the magnitude of any costs caused by conflicts arising from differences in goals values and norms is negligible. For many global business ventures, and intergovernmental civilian or military joint ventures, conflicts in goals, values and cultural norms are rampant, and can have significant costs, as well as some potential benefits, for the project team. Modeling the incremental communication, negotiation and conflict resolution costs associated with cultural and value conflicts as an additional kind of hidden work, while retaining the parsimonious information processing abstraction used by VDT, may provide a means to account for cultural and value conflicts in project teams.

Since Version 2 of VDT with the above limitations was commercialized in 1996, we have developed a series of extensions to the representation and reasoning that extend the applicability of VDT. We describe these extensions in the following section.

4. Ongoing Extensions to VDT

Our intention was always to start with the "organizational information flow physics" of routine projects and then progressively add elements of "organizational chemistry" to the modeling framework. This would allow us to move beyond routine projects and begin to address a wider range of more flexible organizations performing less routine tasks in more dynamic contexts.

It is helpful at this point to position our completed and ongoing versions of VDT in the space of organizations and modeling issues in a "radar chart" (See Figure 2). Starting with the routine project "information flow physics" version of VDT-2, described above, we have extended the representation and reasoning to allow VDT to model less routine work (up the vertical axis from the origin), more flexible organizations (down the vertical axis), more subtle effects of communications and collaboration technology (along the leftward axis) and the "organizational chemistry" of more complex social behaviors (along the rightward axis).

VDT-2 is a reasonable model of project work for which: (1) All tasks in the project can be predefined; (2) the organization is static; and all tasks are pre-assigned to agents in the static organization; (3) exceptions to tasks can be viewed as resulting in extra work volume for the predefined

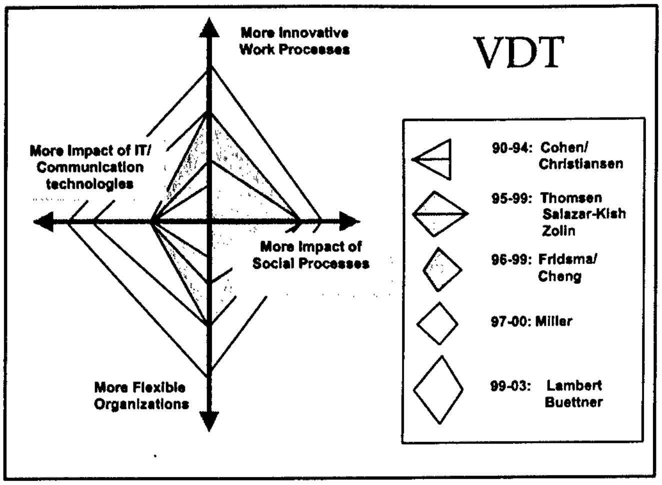

Figure 2 -VDT Research Trajectory

tasks to be carried out by the pre-assigned agents; and (4) agents are assumed to have congruent goals [5], [16]. These conditions fit many kinds of design and product development work. VDT-2 has been commercialized as SimVision™, and is in use by companies in a variety of industries for designing their project organizations [14].

Thomsen's VDT-3 extends the range of work processes that can be modeled, to encompass less routine design or product development work, in which tasks are still predefined, but there can be flexibility in how they are executed [6]. Agents can have incongruent goals causing them to disagree about how best to execute tasks in the project plan. Goal incongruency levels between pairs of agents affect vertical and horizontal communication patterns. VDT-3 has been validated through "gedanken" experiments—thought experiments, in which the model's predictions are compared to managers' predictions of results. It has not yet been prospectively validated—where its prospective predictions are tested against subsequent real project performance data. Salazar Kish [17] and Zolin [18] provided additional extensions that allow reasoning about task overlap and trust between pairs of agents in a project.

Fridsma's VDT-4 attempts to move aggressively beyond the previous VDT limits on work process routineness and static organizational structure [8]. He modeled the highly non-routine work involved in health care delivery for bone marrow transplants and similar complex, multi-specialty medical protocols. He had to relax the constraint that all tasks and assignments are rigidly prespecified. Diagnosis tasks are used to discover the needed repair tasks, and any side effects must be diagnosed and treated contingently. This required significant extensions to the VDT-3 framework. Fridsma extended the information processing micro-theory in VDT-3 to include a variety of more complex exceptions that can cause tasks to be added, resequenced, deleted or reassigned, and agents to be dynamically added to the organization and assigned tasks as needed.

Cheng-Cain [9] extended Fridsma's representation and reasoning to cover dynamic organizational contexts such as time of day, day of week, or agent backlogs, in which agent behaviors and organization structures might change significantly for the non-routine work processes involved in fields like health care delivery. This extended framework has been implemented, internally validated on "toy problems and retrospectively validated against empirical data in several clinical settings.

VDT-2, 3 and 4 implement a simple model of communication tools that transmit information between agents' in-trays. Miller's VDT-5 attempted to extend VDT's communication tool model to include the interactions between task, tool and organization for more complex collaboration technologies that effect not only communication of information between agents, but also the speed and accuracy of information processing by agents working together. Miller laid out the micro-theory to describe how attributes of tools, tasks, agents and organization structure interact, based on extant micro-theory in the CSCW and HCI literatures. Future research will implement these behaviors and then validate them.

A longer-range goal of our work has been to begin modeling even more flexible organizations that can be viewed as dynamically shifting *communities of practice,* in which agents can communicate with anyone they choose inside or outside their local organization. As discussed in the *Limitations* section above, hierarchical exception handling only makes sense in a "boss knows better" organization, typically found in industries with relatively slowly changing technologies. Exception handling via communities of practice is the norm in modern industries with rapidly changing technologies, like software development, microbiology, wireless communications, etc. Moreover, many consulting organizations are already starting to approximate this networked organizational form.

Theories based on Public Goods [19], Transactive Memory [20], and reciprocity in social exchange [21] can be used to describe how these social network links form, and persist or decay, in cyberspace. We have implemented a hybrid software tool combining VDT with the Blanche knowledge network modeling system [15]. In the hybrid VDT-Blanche model, an agent in a project hierarchy that encounters an exception first checks to see whether a supervisor in the hierarchy above it has the necessary skills to help with the exception. If a supervisor has the required skill, the agent uses hierarchical exception handling as in previous versions of VDT. If not the agent will access its knowledge network—i.e., its representation of who it thinks knows what—to find an agent in one of its communities of practice (include a computational agent, like a database, list of FAQs, or other digital knowledge repository) that may be able to help it resolve the exception. If multiple agents send their exceptions to a small number of recognized expert agents in a community, multiple exception-handling tasks will be added to the backlogs of the popular expert agents. As popular agents become backlogged, they take longer to respond, so their value as mentors declines.

We have gathered project organization and workflow data together with data on agents' knowledge networks at two sites, and will be validating the hybrid model in a set of retrospective and natural experiments during 2003 [22], [23]. The hybrid model is already beginning to capture some of the dynamics of exception handling in communities of practice that were predicted by Nasrallah's mathematical model of network-based exception handling [24].

5. FUTURE EXTENSIONS TO VDT

The original VDT framework assumed that project participants worked to the limits of their cognitive capacity, resolving exceptions hierarchically through a static organization structure. Thomsen subsequently added simple economic agency behaviors to model different goal emphases of project team members. Lambert and Buettner are incorporating Public Goods, Transactive Memory, social exchange and other behaviors to model knowledge seeking behavior in communities of practice. However, all of these extensions still implicitly assume that all project team members share basic values and cultural norms, so that agent behavior and project outcomes a limited primarily by the cognitive capacity of the team of agents in the organization.

For many of today's most challenging global projects, these assumptions are clearly unrealistic. Global infrastructure development projects undertaken by groups like The World Bank; global industrial and commercial projects undertaken by multinational companies like Intel, Nokia, Toyota, or Cisco to design manufacture and distribute their products around the world, and multinational peacekeeping forces in countries like Kosovo or Iraq all involve participants whose core values, cultural norms, national legal and political institutions, and work practices differ significantly. In the same way as fast-track, complex projects creates a coordination complexity and associated overhead costs, global projects like the ones above can create significant institutional complexity and associated institutional costs.

Our newest research thrust attempts to represent and reason about important dimensions along which national cultures have been found to differ, and which can affect agent micro-behaviors and interactions in predictable ways. For example, Hofstede [25] found that IBM employees in 61 countries differed significantly in terms of cultural dimensions like *Individualism vs. Collectivism, Degree of Power Distance, Tolerance for Ambiguity, and Degree of Gender-Based Role Differentiation.* These dimensions and others that we are discovering through ethnographic research can be implemented as agent micro- behaviors in the VDT simulation, and then calibrated through a process similar to regression analysis against macro level project outcomes [11]. We have built some simple initial models whose predictions qualitatively match outcomes from a set of U.S.-Japanese joint venture construction projects. We will report on the results of this research at future IEEE conferences.

All of the versions of VDT up to the present assume that agents skills are static and do not change over the duration of a project. This assumption limits the applicability of VDT to relatively short projects for which constant agent skill levels is a reasonable assumption. A related thrust in our ongoing research program attempts to explicitly model different kinds of knowledge flows through which the skills of agents can change—e.g., by formal training, mentoring from a supervisor or a community of practice informant, or agents can increase their competence through trial and error learning experience on-the-job [26].

6. CONCLUSIONS

This paper describes the origins and evolution of VDT, a mature, agent-based computational modeling and simulation framework for designing project organizations. Our experience over the past 15 years has demonstrated that such agent-based simulations can provide extremely accurate predictions of backlogs, delays and quality risks for organizations engaged in complex, fast-track projects. Following extensive validation, the VDT modeling methodology and software tools have begun to be used commercially for designing work processes and organizations on large, complex projects. While early versions of VDT are limited in their applicability to relatively routine "mono-cultural" projects, we have described a set of extensions to the VDT framework that are progressively being validated to enable managers to design more flexible organizations performing less routine work in more dynamic task contexts. Service/maintenance work such as health-care delivery will be the next frontier for systematic Organization Design using agent based analysis tools.

Beyond modeling innovative projects and service/ maintenance tasks, we look forward to being able to model multinational, multi-cultural teams engaged in some of the most challenging and fast-moving projects of the 21st century—global infrastructure and industrial development projects; global health-care and educational initiatives , such as AIDS prevention; multinational peacekeeping; and emergency response. And because knowledge represents an increasingly critical resource for 21st century enterprises, our research to model knowledge dynamics promises to keep VDT-X current and relevant as organizations continue to evolve.

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