THE VIRTUAL DESIGN TEAM

DESIGNING PROJECT ORGANIZATIONS AS ENGINEERS DESIGN BRIDGES

RAYMOND E. LEVITT

Abstract: This paper reports on a 20-year program of research intended to advance the theory and practice of organization design for projects from its current status as an art practiced by a handful of consultants worldwide, based on their intuition and tacit knowledge, to: (1) an "organizational engineering" craft, practiced by a new generation of organizational designers; and (2) an attractive and complementary platform for new modes of "virtual synthetic organization theory research." The paper begins with a real-life scenario that provided the motivation for developing the Virtual Design Team[1] (VDT), an agent-based project organizational simulation tool to help managers design the work processes and organization of project teams engaged in large, semi-routine but complex and fast-paced projects. The paper sets out the underlying philosophy, representation, reasoning, and validation of VDT, and it concludes with suggestions for future research on computational modeling for organization design to extend the frontiers of organizational micro-contingency theory and expand the range of applicability and usefulness of design tools for project organizations and supply-chain networks based on this theory.

Keywords: Virtual design team; project organization design; organization design

MOTIVATION FOR PROJECT ORGANIZATION DESIGN THEORY, METHODS, AND TOOLS

In 1987, Art Smith, the vice president in charge of facilities for a major semiconductor manufacturer, "Micro," was facing a significant organization diagnosis and design challenge. The product life cycle of a new microprocessor is very short – three to six months – before either a competitor or Micro itself produces an even faster microprocessor, at which time the price of that generation of microprocessors must be discounted, so that its gross margin falls significantly from its original level of around 60%. Each production train for a new microprocessor was producing about $1 million of product per hour for Micro early in its life cycle at that time, and a typical fabrication facility (fab) contained three production lines. Any delay in completing a fab on its planned date would cost Micro about 60% of three million dollars per hour of gross margin, seven days per week, 24 hours per day. Thus, on-time completion of a fab was an exceptionally high priority for Micro.

Exacerbating Art Smith's challenge, Micro's manufacturing engineers insisted on waiting until the last possible moment to order the rapidly evolving manufacturing equipment for its fabs, in order to avoid having obsolete equipment in the fabs from day one. Each piece of manufacturing equipment in a fab has different requirements with respect to the geometric layout for moving the silicon wafers between machines, its mounting geometry, the structural support it requires, the fluids and gases to be supplied to it, etc. The detailed design and

---

[1] The Virtual Design Team (VDT) research described in this paper has been supported at different times by the Center for Integrated Facility Engineering and Collaboratory for Research on Global Projects at Stanford University, the National Science Foundation, and the Center for Edge Power of the Naval Postgraduate School. The support of these organizations for the VDT research is gratefully acknowledged. However, the author is solely responsible for the opinions expressed in this paper

DOI: 10.7146/jod.6345

construction of the fab must proceed extremely rapidly and concurrently once the specific new equipment has finally been selected. At the same time, the date at which the fab needs to begin producing microprocessors in quantity is planned far in advance to match the time at which the semiconductor design will be finalized, the photolithography masks for etching the chips will be ready, and the marketing plan will be in place, so that the microprocessors can hit the market in large volume and with high quality at just the right moment.

As Micro's manufacturing engineers pressed Art's team to delay equipment purchases ever closer to the fixed fab completion dates, the fab design and construction projects came under extreme schedule pressure. Micro's response to this pressure was to schedule many highly interdependent tasks concurrently. As the tasks were executed more and more concurrently, the fab delivery projects began to experience an exponentially larger volume of design changes and rework, resulting in delays and quality problems that caused lower-than-expected yields of defect-free processors when the fabs were completed. Facing ever-increasing pressure to accelerate the design and construction of the fabs even further while maintaining high quality, Art Smith wondered how to redesign Micro's fab engineering and construction work processes and organizations to execute these complex and concurrent projects in a controlled manner.

Art's existing design and construction specialists were organized in a "weak matrix" structure, in which specialists were collocated with their disciplinary colleagues and evaluated by their functional managers to facilitate the sharing of technical best practices. Art considered several options:

- Should he reorganize the team into a strong matrix configuration with dedicated and co-located specialists from all key disciplines reporting to, and evaluated by, a strong project manager? How much time would this save on each project, and how might this change impact the capturing and sharing of technical best practices?
- Should he add additional technical staff and/or substitute higher-skilled engineers or craft workers for those currently on the project team, and if so, for which disciplines or crafts?
- Should he add more management personnel, and if so, where in the team and with what kinds of management skills – schedulers, cost engineers, quality control managers?
- Should he re-sequence tasks to be more or less concurrent? How much time could this save and with what impacts on expected cost and/or quality?
- Should he decentralize decision-making to speed up exception handling? What impact might this have on expected quality?

Art could not find any systematic way to help him make these kinds of decisions. Absent any credible tools for designing his project organization systematically, his default – along with the managers of many other large, complex, and costly projects – had become to treat each multi-billion dollar fab design and construction project as a costly, and potentially career-ending, trial-and-error experiment on the path to discovering a way to optimize the organization and work process for fab delivery.

Design Theory, Methods, and Tools for Physical Systems

The engineers and managers working on the chip design and manufacturing engineering side of Micro operated in a world where the designs of their increasingly complex and densely arrayed microprocessors could be modeled, tested, iterated, and refined in advance, using computational analysis tools to predict the performance of a given case in many different dimensions – e.g., logic validation, spatial layout, induced stray current, heat flow, etc. – with considerable accuracy. This systematic and multidimensional model-based design approach for its products was already well advanced and quite routine. What Micro lacked – and what Art Smith challenged a group of Stanford researchers to develop – was a comparable design theory, methods, and tools that Micro's project managers could use to model and analyze a proposed organization and work process case for a fab's design and construction and predict its cost, schedule and quality performance. This would allow his project managers to iterate through analyses of multiple alternative cases of work processes and organizations conveniently and rapidly, and find a case whose performance would best meet the scope, schedule, and resource objectives for each fab project.

The theory and analysis tools for designing semiconductors – along with bridges, skyscrapers, automobiles and airplanes – rest on well-understood principles of physics and operate on continuous numerical variables describing materials whose properties are relatively uniform and straightforward to measure and calibrate. These physical systems could already be analyzed in the early 1900s by solving sets of linear or differential equations that modeled the components of the physical system and their interaction. Starting in the early 1960s, analysis of these systems was increasingly carried out via numerical computing methods that evolved from the World War II use of computers to calculate ballistic trajectories and crack enemy codes. The approach used to develop the engineering science and technology for analyzing and predicting the behavior of physical systems was to:

1. break a large system into smaller elements whose behavior and interactions could be described;
2. embed well-understood micro-physics theory into the elements;
3. attempt to reflect the interactions between elements through constraints (such as constraints that conserve mass or energy, or that maintain consistency between shared element edges in a finite element structural analysis model); and
4. use the vastly more powerful number-crunching ability of computers (compared to human brains) to simulate the system of elements behaving and interacting under various sets of external loads to predict the element- and system-level behaviors of interest.

The result was that engineers rapidly gained the ability to make increasingly accurate predictions of both micro and macro behavior of many kinds of engineered systems. Some of the earliest pioneers in this computational modeling and simulation of physical systems were civil engineers solving large structural engineering problems. For many kinds of structures, design tools can now predict stresses, strains, and deflections under a variety of loading conditions to finer tolerances than the structure can be built.

Design Theory, Methods, and Tools for Organizations

In stark contrast to the sophistication of engineers in modeling physical systems, theories describing the behavior of organizations are still almost exclusively characterized by nominal and ordinal variables, with poor measurement reproducibility. With very few exceptions, the prevailing theories that could be used to describe or predict the behavior of organizations in the late 1980s were verbal descriptions that incorporated nominal and ordinal variables. Theories expressed verbally using nominal and ordinal variables create a significant degree of linguistic ambiguity, so that results of natural or synthetic experiments cannot always be reliably replicated, and contrasting or competing theories are difficult to reconcile or disprove. Thus, developing a quantitative, model-based theory, methods, and tools for designing organizations and the work processes they execute was a daunting challenge.

A key challenge for more systematic design of enterprise-level organizations is that their goals are often vague, diffuse, and contested (March & Simon, 1958). Consequently, it is difficult to evaluate the outcomes of alternative cases, even if one could predict them. However, within such organizations, a specific project encapsulates a subset of the organization’s overall employees or contractors that have been assembled for a relatively well-defined purpose with clear and congruent goals, fixed durations, and clearly defined participants assigned to each of the project tasks. Thus, when faced with the challenge of developing reliable quantitative tools for analyzing the performance of organizations, we believed that the performance of project organizations should be relatively easier to predict and evaluate than the performance of enterprise-level private or public organizations, for which all of these process and outcome variables are much more difficult to identify, measure, predict, and evaluate.

THE BIRTH OF VDT

In the late 1980s, when presented with Art Smith’s challenge, our research group had the intuition that it might be feasible to develop computational analysis tools to model and simulate project organizations with reasonable fidelity through the application and integration of two computer science technologies that were just emerging from computer science research laboratories:

1. **Agent-based simulation** (analogous to the finite element modeling approach for physical systems described above) had been pioneered for organizations in the classic garbage-can model of organizational decision-making (Cohen, March, & Olsen, 1972). Agent-based modeling approaches allow modelers to: specify and embed relatively simple behaviors (e.g., processing quantities of information or communicating with other agents) in a set of computational agents; specify and operationalize a few kinds of interactions between agents and tasks; and run the simulation to generate emergent behavior from the micro-behavior and micro-interactions between agents.
2. **Non-numerical, general "symbolic representation and reasoning techniques"** were just emerging from the laboratories of "Artificial Intelligence"(AI) researchers at Stanford, MIT, Carnegie Mellon University, University of Massachusetts, Xerox Palo Alto Research Center (PARC), and elsewhere to represent and reason about nominal and ordinal variables (as well as numerical variables). These new representation and reasoning techniques allow the inheritance of properties from "parent classes" to "child subclasses or instances" of those classes (e.g., from "workers" to "craft workers" to "carpenters" to "Joe the Carpenter"); this allows the creation of prototypical "classes" that encapsulate the attributes and behavior of tasks, workers, milestones, etc. and thus allow the rapid creation of instances of these classes that inherit all of the class properties and behavior and can rapidly be assembled into a realistic model of the work process. These early AI tools like SmallTalk (Goldberg & Robson, 1983), developed at PARC, and Knowledge Engineering Environment (KEE), developed by Intellicorp, a Stanford spinoff, also supported inferential reasoning about the attributes of objects using "If…, then…" production rules and other forms of computational inference.

The Virtual Design Team (VDT) research was thus initiated in 1987 through Stanford's Center for Integrated Facility Engineering with the goal of developing new micro-organization theory and embedding it in software tools. Our intuition was that agent-based simulation using a combination of non-numerical and numerical reasoning techniques could potentially allow us to model and simulate information flow in organizations and the emergent cost, schedule, and resource outcomes of information processing and communication by and between members of project teams. From the beginning the goal was to develop and validate methods and tools to predict the behavior of organizations executing their work processes with both high fidelity and transparency. The fidelity would give managers the confidence to use the methods and tools to analyze, predict, and optimize the performance of their engineering organizations. Transparency would make the tools easy enough to use and understand that managers could begin to use them in the same way that engineers design bridges, semiconductors, or airplanes – by modeling, analyzing, and evaluating multiple virtual prototypes of the work process and organization in a computer, supporting both decision-making and the development of organizational insights. A key early decision was to use professional programmers and develop drag-and-drop graphical user interfaces to support the robustness, ease of use, and transparency of VDT.

The extremely creative and insightful garbage-can model of decision-making developed by Cohen et al. (1972) was an elegant and simple, yet fruitful, agent-based simulation model of university participants engaged in decision-making meetings. The success of this effort persuaded us, along with many other researchers (e.g., Epstein & Axtell, 1996; Masuch & LaPotin, 1989), to explore the use and limitations of agent-based simulation of organizations. The garbage-can model was a relatively abstract, high-level model of organizational decision-making; Masuch and LaPotin (1989) subsequently extended the model and elaborated both tasks and organizational participants to a much finer-grained level of detail that could potentially have been validated against real micro-organizational behaviors and outcomes (although they did not attempt this kind of validation). These two efforts were important points of departure for our research.

GOALS AND PHILOSOPHY OF THE VDT RESEARCH PROGRAM

Note that the goals of the VDT project were different from those of the two models described in the previous section. Previous organizational modeling and simulation researchers had aimed to use simulations to explore, develop, and test new meso- or macro-level descriptive theory, rather than to emulate and ultimately predict micro-reality. An engineering analysis tool emulates the behavior of its physical elements as accurately as possible and predicts the behavior of the elements and the emergent behavior of the larger system to enable prediction, iterative refinement, and consequential interventions in the design of the product or process being modeled. Our goal was to produce an analysis tool that would support the explicit design of particular project organizations containing workers with defined skill sets and experience levels to execute given work processes under specific and tight resource and time constraints. So we needed to quantify the variables in the model and validate the model's micro-behaviors and predictions extensively for it to become useful for our intended purpose.

By predicting the performance of alternative configurations of an engineered system, model-based simulation can provide engineers or managers with the ability to conduct multiple "virtual trial and error experiments" in which they test – and often "break" – virtual rather than physical prototypes of candidate solutions. Thus, if the modeling methods and tools are easy and transparent enough for managers to develop and explore multiple configurations in a reasonable amount of time, the managers can develop tacit knowledge and expertise about the performance contours of different configurations of a proposed solution by experiencing how the different configurations break in different ways. Accordingly, we decided to call our engineering project modeling and simulation system the "Virtual Design Team" (VDT), by which we meant a computer simulation model of a real design team.[2]

Direct Work and Three Kinds of Hidden Work

VDT was based on the notion, articulated by Herbert Simon (1947), refined by Jay Galbraith (1974), and extended and quantified by our research team, that the first-order determinant of an organization's success is its ability to process all of the information associated with *direct work* as individuals or groups complete their assigned tasks; and *exceptions* arising from missing or incomplete information needed by a worker to complete an assigned task. Each exception requires the worker to seek advice from a more knowledgeable person, generally a supervisor somewhere up the hierarchy. Galbraith had proposed this idea as early as the 1960s, but his formulation of the problem was descriptive and qualitative and thus could not be used to make specific predictions about when and where the quantity of information to be processed in a specific work process would overwhelm one or more participants in the organization assigned to execute that work process. VDT quantified, extended, and validated Galbraith's information-processing view of organizations conducting work and generating, escalating, and resolving exceptions to encompass a broad range of project-oriented work processes and organizations. In refining and elaborating Galbraith's notion of exceptions, we distinguished between:

- ***Functional exceptions*** arising from incomplete technical knowledge, which a worker might escalate to a more expert functional supervisor in his or her discipline who would be required to do "supervisory work" to resolve the exception
- ***Project exceptions*** arising from incomplete information at the interfaces between interdependent tasks performed by peers in other disciplines, which a worker would need to resolve by doing "coordination work" with the interdependent party – what Thompson (1967) referred to as "mutual adjustment of reciprocal interdependency"
- ***Institutional exceptions***, arising in cross-cultural global project teams from the need to resolve differences in goals, values, and cultural norms between project team members from different national institutional backgrounds (Scott, 2008). Managers attempting to resolve this kind of exception would need to perform "institutional work." We set institutional exceptions aside for subsequent research and focused initially on modeling functional and project exceptions.

---

[2] The phrase "virtual team" subsequently began to take on a different colloquial meaning in the organizational literature – a geographically distributed team and/or one comprised of members from multiple separate organizational entities.

The intuition behind the 20-year VDT research program was that direct work, supervisory work, coordination work, and institutional work could all be viewed as quantities of information to be processed by the workers and managers in an organization. If one could represent and quantify the information-processing demand generated by a given work process, and the information-processing capacity of the workers and managers in an organization configured in a particular way, a simulation model of the flow of information to perform direct work and generate and handle exceptions through a project team would provide a first-order estimate of whether or not a given configuration of the project organization possessed the appropriate information-processing capacity in the correct places within the project organization to:

- process the information required to execute the direct tasks;
- provide adequate, high-level technical information-processing capacity in the right places to resolve technical exceptions; and
- have sufficient slack information-processing capacity to allow interdependent workers to coordinate cross-disciplinary reciprocal interdependencies that might arise in the execution of the project.

In this respect, VDT is simply a micro-level, more detailed and quantified form of the qualitative, rule-based macro-information processing contingency theory framework used to diagnose organizational misfits in Burton and Obel's (2004) book *Strategic Organizational Diagnosis and Design* and its accompanying *Organizational Consultant* software tool.

Organizational Physics, Chemistry, and Biology

We viewed this analysis of the project organization's information-processing capacity vs. information-processing demand as a first-order "information flow physics" approximation of the organization's ability to execute the project. In this respect, VDT is similar to Isaac Newton's Second Law of Motion, which predicts the motion of an object subject to one or more force vectors – but without considering effects like friction or relativity – accurately enough for many practical purposes. If the physics of a bridge are inadequate, it collapses the first time the wind blows too hard, like the first Tacoma Narrows Bridge. Similarly, if the information-flow physics of a project organization are wrong, the organization encounters cost overruns, schedule overruns, and quality risks in a way that Galbraith predicted qualitatively from his observations of aerospace projects in the 1960s. VDT assumes uniform and high levels of motivation by all project actors and ignores the potential for goal conflict. A more refined analysis of the goals and motivation of actors – which we excluded from our first-order physics model – can be viewed as "organizational chemistry." If the organizational chemistry is wrong, the organization eventually fails through slow processes analogous to "corrosion" of physical systems. Finally, if the "organizational biology" is wrong, the organization cannot grow new knowledge to enhance its performance over time or reproduce itself.

As we discuss later in this article, subsequent versions of our VDT model began to incorporate some aspects of organizational chemistry and organizational biology. This paper will focus primarily on the information flow physics of our first VDT prototype, "VDT-1."

VDT MODELING AND SIMULATION APPROACH

We directed our initial focus toward project organizations engaged in semi-custom engineering work under tight time constraints, such as those encountered by Micro in our example above. For such organizations, we could assume a relatively high level of congruency of goals, culture, and values, so that institutional work is negligible and can be ignored. However, performing highly interdependent work under tight time constraints creates a significant amount of coordination work as interdependent tasks increasingly overlap one another in time. Primary emphasis was on modeling the sources of interdependence in project workflow and the way in which exception handling and coordination took place within organizations assigned to do such project work.

VDT incorporated the kind of quantitative reasoning about decision-making demand and capacity used in the garbage-can model (Cohen et al., 1972) as well as the kind of non-numerical reasoning about task assignments, skill sets of participants, etc. used in Masuch and LaPotin's (1989) model. VDT uses symbolic reasoning about nominal and ordinal variables (e.g., the degree of fit between the worker's skill set and skill level vs. the technical complexity and uncertainty of the task to which the worker is assigned) to set parameters for numerical variables (e.g., task processing speeds and expected error rates) in a quantitative, stochastic, discrete event simulation. In the remainder of this section we provide an overview of the representation and reasoning in VDT.

Modeling a Project in VDT

A VDT user assembles a work process and organization configuration (called a "case" in VDT) using a graphical "model canvas" to provide maximum transparency of the modeled case for the manager and model developer.

- **Project organization participants** are rapidly created by dragging and dropping team members from a graphical palette onto the model canvas as instances of classes defining the behavior of three kinds of employee roles (project managers, sub-team leaders, or sub-teams).
- Similarly, specific **tasks**, milestones and meetings are created as instances of classes (e.g., milestones, tasks, and meetings) by dragging and dropping the appropriate objects from the palette onto the model canvas.
- Several kinds of **relationships** between actors and other actors (i.e., supervisory relationships), between pairs of tasks (e.g., sequential interdependence, information exchange requirements), and between actors and assigned tasks (e.g., primary or secondary task assignments, meeting participation) are created by dragging and dropping relationship objects from the palette onto the model canvas and connecting them between the appropriate actors or tasks.
- **Contextual variables** such as overall project complexity and uncertainty, the strength of the functional vs. project dimensions of the matrix, the prior experience of team members working with one another, etc. are entered into a property table prior to simulation.
- **Agent micro-behaviors** for different types of work – e.g., hardware engineering vs. software engineering – are defined using a set of small matrices stored in a "behavior file." The rows and columns in these behavior matrices are typically nominal or ordinal variables that describe actor, task, or context properties – e.g., an actor's *Application Experience* (the level of experience the actor has working on this type of task, with values of low, medium, or high) and the actor's *Skill Level* in the profession involved (say *Structural Engineering*, rated as low, medium, or high). The entries in each cell of this 3x3 matrix are numerical values used in the discrete event simulation, e.g., a number that is the ratio of the actor's information-processing speed relative to a nominal actor who has medium application experience and medium skill of the type required to perform this task. In our research we developed and validated two predefined behavior files: the default behavior file developed from construction, aerospace, and other kinds of hardware engineering; and a second optional behavior file with significant differences that more accurately describes agent micro-behavior for software engineering. These matrices are contained in a text file and can easily be edited and modified to model different kinds of agents engaged in other kinds of work processes. The ability to edit the behavior files easily has been exploited by many of the researchers whose experiments are described in the section on "Using VDT to Develop Meso- and Macro-Organization Theory."

The VDT model canvas for the project manager's initial "Baseline Case" of the work process and organization to complete the design of a biotech manufacturing plant is shown in Figure 1.

Simulating Project Organizations in VDT

The Virtual Design Team simulation system is an agent-based, computational, discrete event simulation model of information flow in project organizations. As VDT actors attempt to complete their direct work, task attributes such as complexity and uncertainty and actor attributes such as skill level and experience are evaluated and compared. VDT reasons qualitatively about non-numerical attributes such as individual team members' skills and experience, task attributes like work volume, complexity, and uncertainty, and ordinal organizational variables such as the level of centralization and formalization (high, medium, or low) to set numerical values like actor information-processing speeds, and exception rates for functional and project exceptions used in the quantitative discrete event simulation. VDT simulates each of the team members processing its assigned tasks, once the tasks' predecessors have been completed, and generates functional and project exceptions stochastically using Monte Carlo sampling methods.

Actors are more likely to generate exceptions when confronted with a task for which they do not possess the requisite levels of skills or experience. Depending on the advice of the manager to whom an exception was delegated, the actor may need to rework the task that generated the exception partially or completely. Actors may be required to attend to communications from other actors and may need to attend scheduled meetings, all of which consume the actor's information-processing capacity. Moreover, failure of an actor to attend to a communication within a specified length of time (after which the communication is moot) or to attend an assigned meeting increases the probability of exceptions occurring downstream. These kinds of communication failures thus produce second-order effects such as increased downstream coordination and rework costs.

A detailed explanation of the objects, attributes, relationships, and behavior in VDT is beyond the scope of this paper. Interested readers are referred to Jin and Levitt (1996).

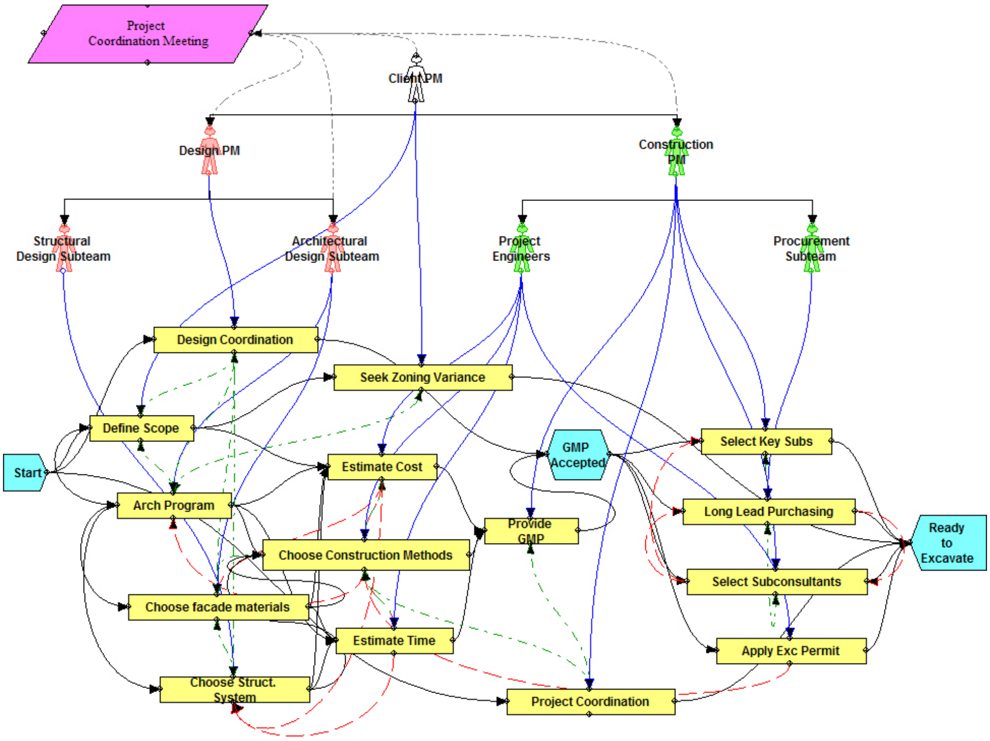

Fig. 1. VDT/SimVision Graphical Model Canvas

VDT thus builds on and quantifies Galbraith's (1974) information-processing view of project teams and views both the direct work and resulting coordination work on a project as quanta of information to be processed by assigned actors who have only "boundedly rational" (March & Simon, 1958) information-processing capacity. It simulates the project team executing tasks and coordinating to resolve exceptions and interdependencies. The simulation of a project organization executing its tasks generates a range of outputs that predict the emergent performance of the organization at both the individual actor/task level and the overall project level: duration, production costs, coordination costs (communication, rework, waiting), and several measures of process quality.

Iteratively Refining a Project's Organization and Work Process Using VDT

The approach used by a manager like Art Smith to design an organization using VDT starts by having the manager generate a plausible first cut at the organization and work process for his or her project based on his or her prior project experience and/or judgment. The manager can then simulate this first cut "Baseline Case" to see how well its predicted schedule, cost, and quality risk meet project goals. Figure 2 shows a Gantt chart to visualize the predicted schedule performance of the baseline organizational case for the biotech design project shown in Figure 1. The Gantt chart shows this biotech project will achieve its completion milestone of "Ready to Excavate" (black diamond on the last line of the Gantt chart) in early March of 2007, long after its planned early December completion date (green diamond on the final line).

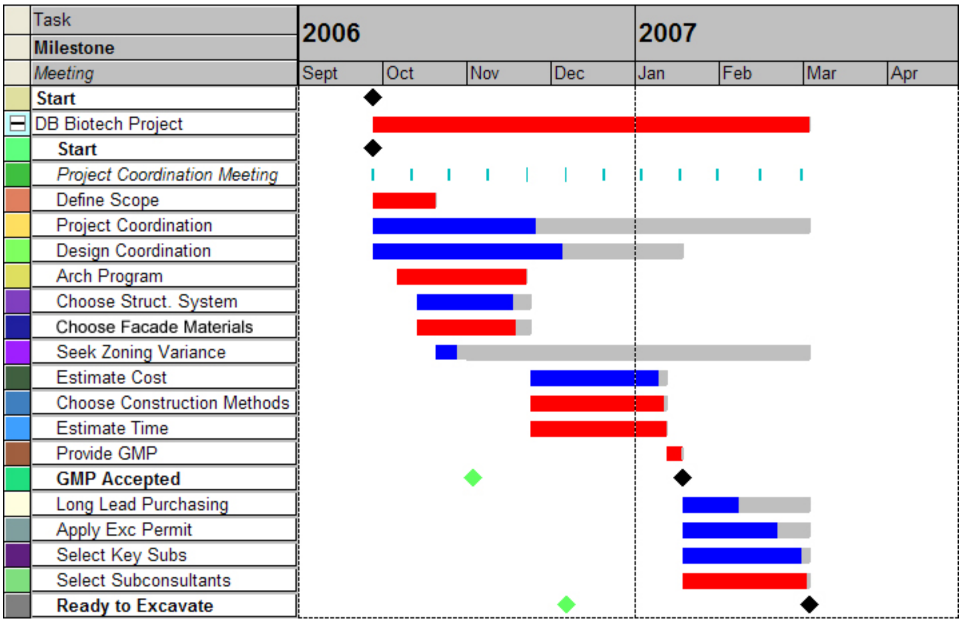

Fig. 2. VDT/SimVision Simulation Schedule Output

The VDT model canvas[3] shown in Figure 1 was used to create and visualize the work process and organization model for a project to accelerate the design of a biotech manufacturing plant for a recently approved cancer therapy drug. Tasks, milestones, and organizational participants are dragged and dropped from the model palette on the left onto the canvas and named. They can then be connected into relationships such as: task-activity successor links, shown as black arrows; the supervisor-subordinate hierarchical relationships shown in the project organization chart; or the blue task assignment links between participants and their assigned tasks by dragging and dropping the appropriate connector onto the model canvas and connecting the ends to the attachment points on the desired objects. The purple object at the top left is a weekly two-hour coordination meeting, attended by the project manager and sub-team leaders connected to it with dashed arrows. Numerical project-level parameters for technical and cross-functional error probabilities, information exchange frequency and noise, and low, medium, or high ordinal values for organizational parameters such as matrix strength, team experience, centralization, and formalization are entered directly into the property table at the top left. Clicking on any object displays its properties (e.g., team members' skills and skill levels, tasks' total work volume, etc.) in the property pane, where they can be input and changed.

---

[3] VDT was commercialized in 1996 as SimVision™. The VDT modeling canvas was a slightly more primitive, but essentially similar, version of the SimVision modeling canvas shown in Fig 1. (SimVision is licensed by ePM of Austin, Texas http://epm.cc for academic use or professional application).

If this were his project, Art would want to understand why the project was predicted to be so late. The bars shown in red on the Gantt chart indicate critical path[4] tasks whose duration determines the final completion. Blue bars with gray “float” shown after them are non-critical tasks whose duration will not impact project completion. It would be helpful if Art could determine which organizational participants were predicted to be backlogged with information overload in the baseline case. Figure 3 shows the VDT prediction of the Information-Processing backlogs in Full-Time Equivalent (FTE) person-days for all of the positions in the project organization.

Art could then make up a second project case to explore the implications of an intervention such as: increasing the capacity of one or more of the most heavily backlogged sub-teams *(Architectural Design Team and Construction PM)* responsible for tasks that lie on the critical path; increasing the skill level of the workers already assigned to those tasks (by substitution of more experienced team members or training of existing team members); changing the sequence relationships between tasks on the critical path so that they are performed concurrently rather than sequentially; etc. He could then simulate this second case to evaluate its performance in terms of project objectives, and compare its performance to the baseline case to see whether this intervention to the baseline case predicted a better or worse trade-off among his project objectives. Figure 4 compares the schedule for an intervention that adds 0.5 FTE to the Architectural Design Team and 1.0 FTE to the Construction PM to the Baseline Case.

This figure shows the VDT schedule prediction for the Baseline Case of the biotech plant example shown in Figure 1. The client wanted the project to be ready for construction by the first week in December – the green “Planned Milestone Date” diamond on the final Ready to Excavate row of the Gantt Chart – in order to get the foundation built before the rains begin. VDT predicts that the Baseline Case will be completed in mid-March, about three months late, shown by the black “Predicted Milestone Date” diamond at the lower right. This is clearly an unsatisfactory case, so the manager will need to model and simulate possible interventions in the project scope, work process, and/or organization to find a case that will allow him or her to complete this project on time.

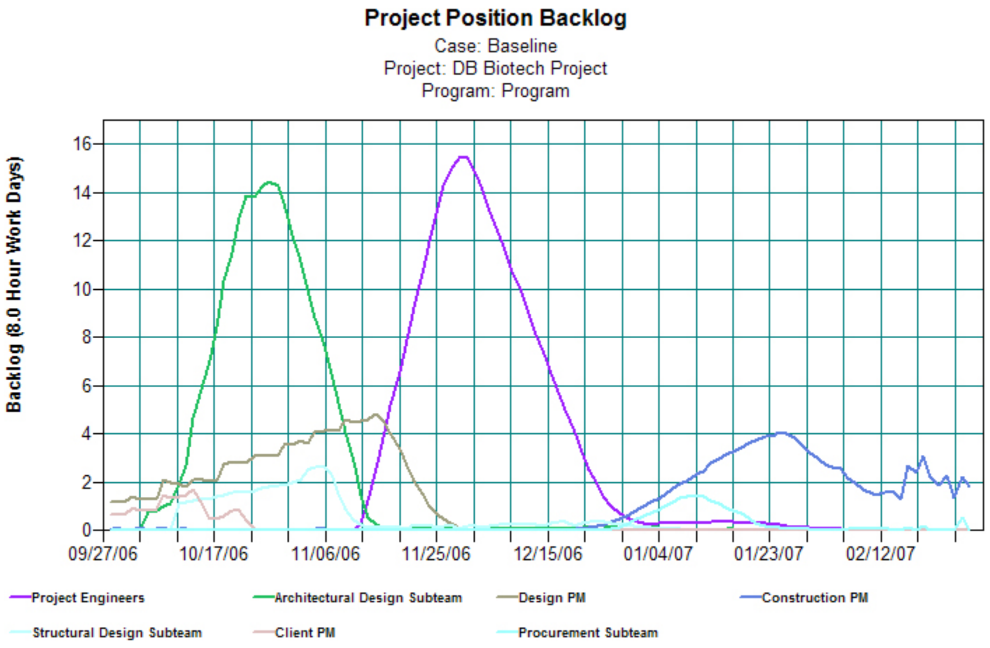

Fig. 3. Predicted Information-Processing Backlogs

This chart shows VDT’s predictions of the expected full-time equivalent (FTE) person-days

---

[4] The “critical path” is the path through the longest chain of sequentially dependent tasks in the project. The durations of activities that lie along the critical path determine the project duration, since any change in the duration of one of these tasks will impact the final completion date of the project.

of backlog for all of the positions shown on the organization chart in Figure 1. Note that the Architectural Design Team is predicted to be backlogged about 14 FTE-days early in the project and the Construction PM is predicted to be even more backlogged in the latter part of the project. When backlogs get beyond about two FTE days, managers focus on recovering from their own backlog of direct work and may fail to respond to coordination requests before they time out and miss scheduled meetings, causing quality risks to rise. Adding extra capacity or raising the skill levels of the persons assigned to one or both of these two positions will likely improve the schedule and may also have implications for the project's process-quality risks.

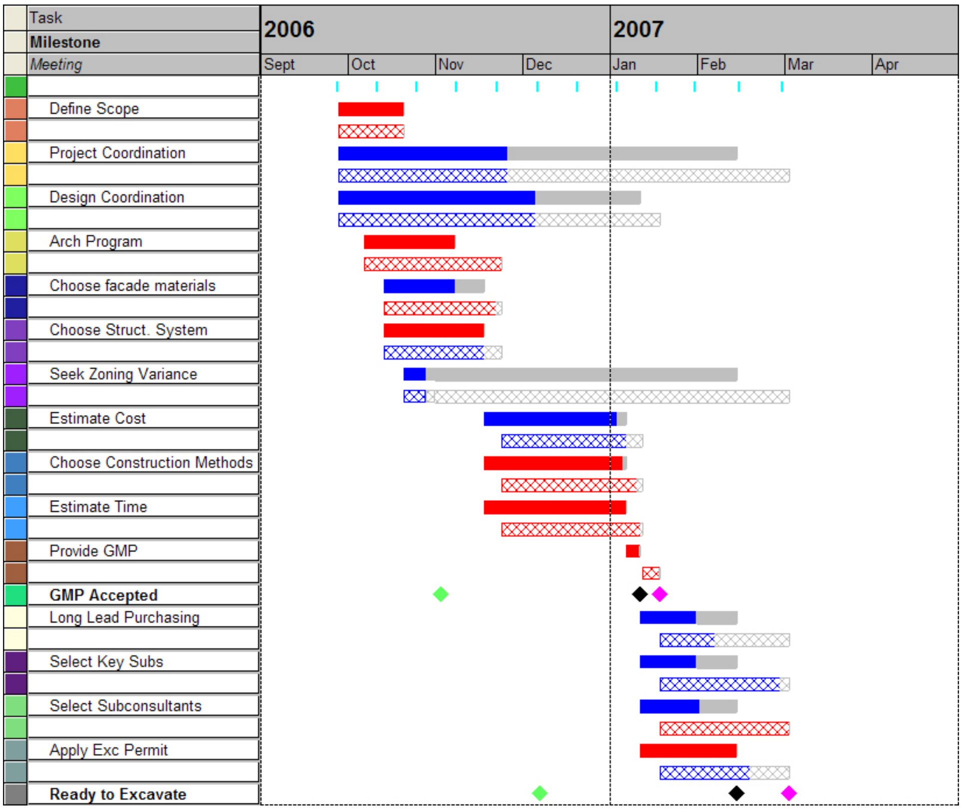

Fig. 4. Exploring the Impacts of an Intervention on Project Schedule

This Gantt chart shows the effect of adding 0.5 full-time equivalents (FTEs) staffing to the *Architectural Design Team* and 1 FTE to the *Construction PM*. The task durations and start and end times for the modified case are shown as solid bars and can be compared to the original Baseline Case shown as hatched bars; the milestone dates for the new case are shown as black diamonds, and those for the Baseline Case are shown as purple diamonds; the client's planned milestone dates are shown as green diamonds. A glance at the bottom line – the Ready to Excavate completion milestone – shows that this intervention will shorten the project by about three weeks from the Baseline Case, but will still complete much later than the planned completion date (the green diamond on that row of the Gantt chart). Scanning the bars to see where the time savings were achieved and where the critical path now lies reveals that the biggest impacts of this intervention case were to shorten the duration of the two critical path tasks, *Arch Program* and *Choose Façade Materials*, performed by the *Architectural Design Team*. Note that *Choose Façade Materials* is now predicted to be non-critical. Similarly the durations of the tasks, *Select Key Subs* and *Select Subconsultants*, performed by the *Construction PM*, have been shortened. *Select Subconsultants* was previously on the critical path, but both tasks are now non-critical.

Thus far, we have only considered schedule goals; a more thorough analysis must also assess whether desired cost and quality metrics have been achieved. These outputs are shown schematically at the right of Figure 5. Unacceptable performance in terms of cost or quality risks can be addressed by different kinds of managerial interventions. For example, unacceptably high levels of functional quality risk can usually be addressed by increasing the level of centralization of decision-making to *High* (i.e., most exceptions will now be reviewed by project managers instead of sub-team leaders). However, this can introduce delays if a backlogged project manager takes longer to attend to, and resolve, exceptions. Organizational contingency theory (Burton & Obel, 2004) asserts that this trade-off depends on several contextual variables, such as the span of control of the project organization (how many sub-team leaders report to the manager, and how many workers report to each sub-team leader). The higher the span of control at each level, the larger the number of workers reporting to that manager, and hence, the greater the expected frequency of exceptions landing in the managers' in-basket. If the project organization has a high level of centralization – i.e., most exceptions must be dealt with by the project manager – then a large span of control, coupled with a relatively poor match between the workers' skills and the complexity of the tasks they are working on, will result in a high likelihood that the project manager will get backlogged and become very slow to handle exceptions.

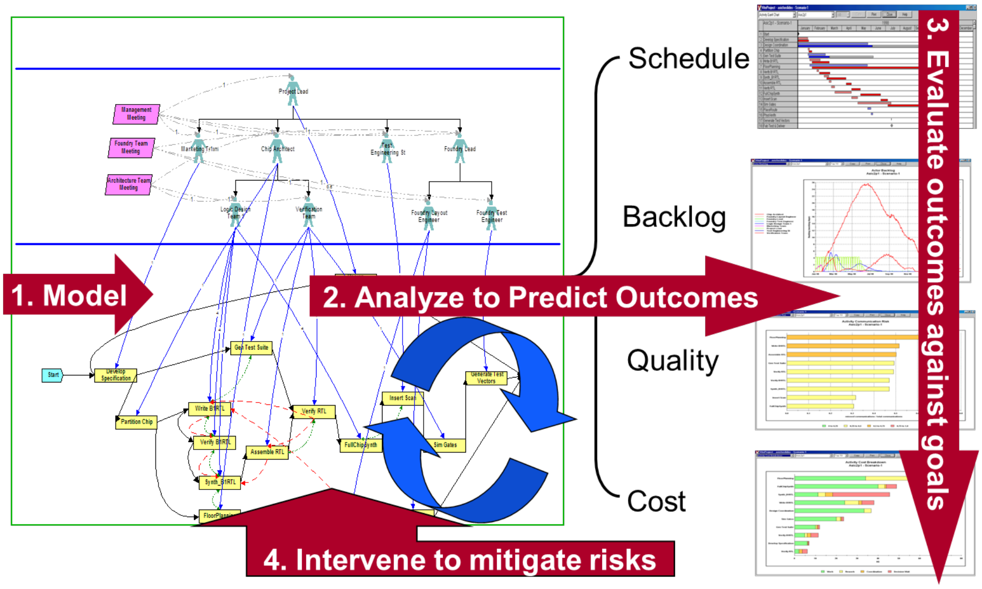

Fig. 5. A Process Model for Simulating and Evaluating Project Outcomes

High backlogs do not only affect project schedule. When managers become backlogged and fail to handle exceptions within a reasonable timeframe, subordinates begin to "delegate by default" – i.e., they use their best judgment to decide what to do about an exception. When this occurs, the level of centralization of decision-making in the organization has effectively been lowered by default rather than by design. VDT models these "delegation by default" instances as increasing the "functional quality risk" for the tasks whose exceptions have been delegated by default to low levels of decision-making.

Similarly, cross-disciplinary coordination can break down if workers who are asked to respond to coordination messages fail to respond within a reasonable period, resulting in increased "communication risk" for the task whose coordination was not completed. Unacceptably high communication risk can be addressed by increasing the project organization's matrix strength. This is achieved in practice by co-locating team members of different functions in a project cluster and having the project manager evaluate them in terms of project objectives rather than having a functional manager evaluate them based on each discipline's technical criteria. Note that increasing the organization's matrix strength will decrease communication quality risk, but it can increase technical quality risk because functional workers are no longer co-located with their functional peers.

These are precisely the kind of difficult and opaque organizational trade-offs that can be explicitly and transparently explored by a manager using VDT/SimVision. A quantitative simulation tool like VDT/SimVision provides **quantitative resolution** of the **qualitative**

indeterminacy that is otherwise inherent in these trade-offs. Proceeding iteratively in this way, the manager can explore the implications and trade-offs among schedule, cost, and quality outcomes resulting from dozens or even hundreds of alternative cases of the organization and work process in order to find one or more alternative cases that come closest to meeting project goals. If the project goals cannot be achieved through changes in the work process or organizational structure – which is often the case for projects with very aggressive schedule goals – the manager can explore reducing the scope of the technical deliverables for the project. In many cases, it may be more advantageous to the client to scale down the project's scope in ways that do not detract from its primary function in order to have at least a scoped-down version of the product ready by a fixed date such as a tradeshow or a regulatory deadline. This will shorten task durations and possibly eliminate some tasks, positions, and/or staff members from the project team. In the biotech design case illustrated above, the client ultimately found that the desired early December completion date could not be met with any feasible configuration of the work process or organization, and therefore decided to use a prefabricated metal building for the biotech facility instead of having the architect design a custom building for the plant. This greatly reduced the scope of the architectural design tasks and resulted in a predicted early December completion date, which the team was able to meet.

The process of modeling, simulating, and evaluating predicted outcomes against project goals, and iteratively refining and testing alternatives in an attempt to better meet project goals, is summarized in Figure 5. By iteratively modeling, analyzing, and evaluating alternatives, and exploring the impact of successive interventions, a manager can rapidly explore dozens or hundreds of cases of the work process and organization, and home in on one or more cases that provide the best trade-off among scope, schedule, cost, and quality project objectives.

VALIDATION OF VDT

In their paper on validation of computational organizational models, Burton and Obel (1995) cite Cohen and Cyert (1965), who asserted that "...even though the assumptions of a model may not literally be an exact and complete representation of reality, if they are realistic enough for the purposes of our analysis, we may be able to draw conclusions which can be shown to apply to the world." Thus, some models must be rather realistic; some need not be. As explained above, the primary goal of the VDT research was to develop a computer simulation model that could emulate the behavior and outcomes of real-world project teams executing complex work processes accurately enough to guide managerial interventions. Thus, it was important to us that we carefully validate and calibrate the non-numerical and numerical parameters of the model's inputs and outputs so that we could eventually credibly claim that VDT provides accurate first-order predictions for real-world projects.

By operationalizing and extending Galbraith's information-processing abstraction in the VDT computational model, and focusing on semi-routine project organizations – an "easy corner" of the space of all organizations – we developed several versions of VDT and validated the representation, reasoning, and usefulness of our computational "emulation" models using the rigorous validation trajectory shown in Figure 6 (Kunz, Christiansen, Cohen, Jin, & Levitt, 1998; Levitt, Cohen, Kunz, Nass, Christiansen, & Jin, 1994; Levitt, Thomsen, Christiansen, Kunz, Jin, & Nass, 1999; Thomsen, Levitt, Kunz, Nass, & Fridsma, 1999). The large background arrow charts the validation trajectory from the lower left to the upper right of this diagram, showing how we successively validated the Reasoning, Representation, and, finally, Usefulness of VDT.

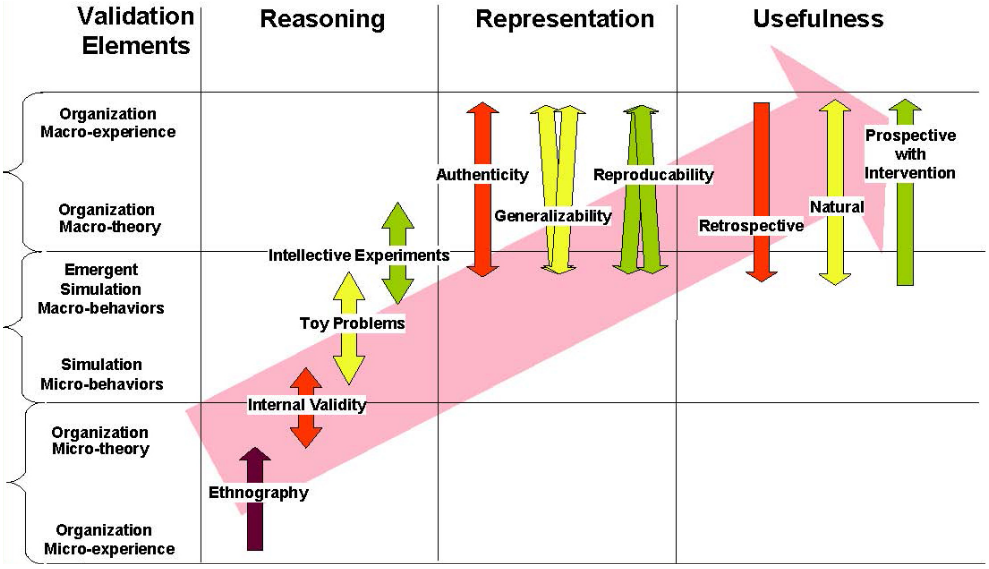

Fig. 6. Validation Trajectory for VDT Project Organization Simulation Model
Source: Thomsen et al., (1999).

Validation of Reasoning

Phase 1 of the validation focused on the model's "reasoning" – the parameters and algorithms that simulate information-processing and exception handling by agents in the model. This phase required, first, that the micro-behavior of workers and managers in the model be based on solid ethnographic research by our research team or others. Thus, we began our research in 1988 by using ethnographic methods involving shadowing of project team members and their managers for weeks at a time to gather quantitative data on low-level actor and task behaviors, such as the length of time it typically takes managers at different levels to resolve exceptions, the rules project team members use for deciding the order in which to attend to items in their in-baskets, the effect on project error rates of missing meetings, and so on. This ethnographic research was reported in Cohen (1992) and Christiansen (1993). Next, we needed to validate the accuracy of the model's predictions. To do this, we embedded these validated chunks of agent micro-behavior in the simulation agents and designed a set of "toy" problems – small idealized cases involving a handful of tasks and positions for which we could determine the correct outcomes by hand calculation – to validate that we had correctly embedded these behaviors. The third step in evaluating the reasoning (Christiansen, 1993) was to design "intellective" experiments (Burton & Obel, 1995) in which we attempted to replicate the predictions of information-processing organization theory developed by others, drawing on the encyclopedic compilation of organizational contingency theory in Burton and Obel (2004).

"Docking" two or more computational models of organizations against the same set of data to compare their outcomes has been proposed as a particularly insightful form of validation of the respective models' reasoning. Several researchers have used VDT/SimVision in docking experiments with Burton and Obel's (2004) OrgCon, including the following: Carroll, Gormley, Bilardo, Burton, and Woodman (2006) docked SimVision against OrgCon to study project work processes and organizations at NASA, yielding valuable insights for the NASA managers; and Cardinal, Turner, Fern, and Burton (2011) carried out an ambitious experiment involving a three-way triangulation of SimVision against both OrgCon and data from a set of case studies of new product development, and were able to develop new contingency theory propositions for the design of product development organizations. Similarly, Carroll and Burton (2012) carried out a three-way docking using SimVision to optimize project organization design; OrgCon to diagnose the goodness of fit of the elements of NASA's enterprise's organization and context; and the *Design Structure Matrix* tool (Steward, 1981) to analyze task interdependence and reorder tasks to minimize design cycles. Each of these experiments demonstrated the feasibility of using multiple organizational analysis tools side by side to design project organizations, and they highlighted the complementarity of the tools involved for shedding light on different aspects of the design of the project organizations and their work processes.

Validation of Representation

The second phase of the validation assessed VDT's semantics and syntax in terms of their "representational validity." This consisted of validating its "authenticity" – i.e., whether the terminology in VDT was easily and consistently understood by practitioners – the "generalizability" of the VDT modeling concepts across different kinds of projects, and the "reproducibility" of models – i.e., whether different modelers would produce similar VDT models of the same project. Cohen (1992), Christiansen (1993), and Thomsen, Kwon, Kunz, and Levitt (1997) all contributed to this phase of the validation by working with managers of real projects and observing when names of objects, relationships, or other model inputs and outputs did not match the manager's colloquial understandings of those terms (e.g., we changed the nomenclature of "Role" to "Position"; "Actor" to "Person"; "Activity" to "Task"; "Exception" to "Error"; etc., as a result of our validation of the model's authenticity. We modeled several different kinds of engineering projects, including oil refineries, electric power substations, biotech manufacturing plants, semiconductor fabs, software development efforts, satellite launch vehicles, satellites, and microprocessors in different phases of the validation. In addition to the research students who formally validated the representation, reasoning, and authenticity of models, about 50 MS-level graduate students per year over a period of about eight years used our evolving VDT modeling and simulation methods and tools in project organization design classes in which they modeled more than 100 other projects in a variety of different domains and provided valuable feedback to the research team on representational issues.

Validation of Usefulness

The final phase of the validation focused on the model's "usefulness" – the extent to which project management practitioners would eventually come to have enough confidence in VDT's predictions to begin using the model to support organization design proactively on their projects. This phase involved modeling and attempting to emulate the outcomes of real-world projects – first retrospectively, then in real-time natural experiments. Cohen (1992) retrospectively modeled the repairs to a series of electrical substations damaged by the 1989 Loma Prieta earthquake that had to be urgently repaired, and adjusted numerous parameters of the model to replicate this past experience. Christiansen (1993) carried out additional retrospective validation of the model's predictions, in which he replicated the design of the Statfjord subsea oil modules that had been designed and installed under extreme time pressure in Norway's North Sea oil fields and calibrated the model parameters associated with quality risks.

Thomsen (1998) conducted the first real-time validation of VDT on Lockheed's attempt to build its first commercial satellite launch vehicle. Lockheed had been building roughly comparable launch vehicles for military missiles for more than two decades, so they viewed this project as semi-routine at this point. However, to meet the needs of very demanding clients, they were attempting to develop a commercial satellite launch vehicle in just one year – one fifth of the time that it had historically taken the company to develop comparable launch vehicles for Navy missiles. The VDT research team was asked by the National Science Foundation, which had provided the bulk of the funding for the VDT research, to study the Lockheed Launch Vehicle One (LLV1) project in real-time and predict its outcome. The project commenced in early 1995 and was scheduled to be completed and launched by the end of that year.

By March of 1995, a team consisting of Jan Thomsen, John Kunz, and Yul Kwon developed a VDT model of the organization and work process for this project and ran the simulation. The simulation predicted that LLV1 would not be completed until mid-April of 1996. Moreover, the VDT model of LLV1 predicted extremely high quality risk for the cable harnesses, a component which Lockheed had decided to outsource to an East Coast company in order to develop its capability for "agile manufacturing" and to save a modest amount of cost.

The launch vehicle was completed and launched about four months late (within a few days of the date VDT had predicted a year earlier). The launch vehicle almost immediately "departed controlled flight" and had to be detonated by the Air Force safety officer. Analysis of telemetry data from the failed launch vehicle indicated that the most likely cause of failure had been a cable from one of the cable harnesses that had been misrouted and got too close to a hot area of the launch vehicle, which melted its insulation and caused a short-circuit – a literal and figurative quality meltdown! As a senior Lockheed manager stated, "The launch vehicle was insured; the satellite was insured; everything was insured except Lockheed's reputation" (Thomsen et al., 1997).

At the time that the Stanford VDT team made its prediction of the completion date and quality risks for LLV in March of 1995, neither they nor the Lockheed managers involved had sufficient confidence in the VDT predictions to intervene proactively in the organization or work process. This extraordinarily accurate natural experiment to predict the outcomes of a real-time project organization was thus a breakthrough moment in the validation of VDT. After this validation exercise, the VDT research team was invited to work with the manager of a subsequent Lockheed satellite project in a different division of Lockheed. This manager helped to build the model and relied on the model's predictions to make a series of prospective managerial interventions that helped keep that project on schedule and within quality bounds (Kunz et al., 1998).

Other researchers subsequently began to use VDT in an "action research" mode for prospective design of project organizations in real-world situations. Carroll et al. (2006) utilized SimVision along with other approaches at NASA to predict project performance, diagnose project risks, and support organizational redesign. This project had a happier – if much less dramatic – ending. Several lessons were learned from this experiment:

- First, similarly to Lockheed's managers, the intuitions of the professional engineers at NASA about the outcomes of alternative project organizations designs was not as good as they believed; their solution was shown to be infeasible using the tools of organizational analysis.
- Second, NASA avoided some headaches and retrofitting that it would have incurred without the tools and their application. That is, NASA avoided an opportunity loss.

Tools can make a difference in the analysis of organizational configurations that have already been designed using managers' intuitions and judgment, or have been copied exactly from previous projects. They can also be used in the upfront design of a baseline organization. The NASA project was a very complicated multi-organizational, multi-location project design where the tools helped managers avoid adverse outcomes.

As Michael Schrage (2000) describes in his book, *Serious Play*, creating a shared language and a visual "blackboard" with which project team members can explore and discuss alternative configurations is valuable in facilitating brainstorming and analysis, even absent any predictive power of the language and visualizations being used. However, when tools like spreadsheets or organizational simulations are able to make plausible predictions about financial outcomes or project organizational outcomes, respectively, the team's decision-making process is literally transformed to a new and much more productive level of brainstorming and decision-making, which Schrage calls "serious play."

Starting in about 1996, after the VDT software had been commercialized as SimVision, consultants at Vité Corporation (the company which initially developed the SimVision prototype under license from Stanford University) and subsequently ePM, LLC, which acquired the rights to the SimVision software and began using the software in its project organization design consulting practice in about 2000, have modeled hundreds of real-world projects with very demanding clients and have demonstrated the usefulness of this model in practice over more than a decade.

By rigorously validating every aspect of VDT in these three ways through all of these validation steps, we were able to generate sufficient confidence in the predictions of our theory and tools that managers in several companies and governmental agencies began using the software to design or redesign their project work processes and organizations prospectively, based on the predictions of this organization modeling and simulation design approach. Our VDT theory and analysis tools for project organizations had thus begun to enable true "organizational engineering" of project organizations that could be assumed to have relatively congruent goals, and were executing relatively routine – albeit complex and fast-paced – engineering-design and product-development work processes.

USING VDT TO DEVELOP MESO- AND MACRO-ORGANIZATION THEORY

Once VDT had been thoroughly validated, researchers at Stanford and elsewhere began to use the simulation tool as a new kind of virtual synthetic organizational experiment to develop, validate, and extend organization theory.

Toward an Organizational Reynolds Number

The first effort of this type was a project that involved several undergraduate students over a number of years attempting to develop an organizational analogy to the dimensionless Reynolds Number[5] that characterizes fluid flow as laminar vs. turbulent in fluid mechanics. Our intuition was that a similar dimensionless number might be found for demarcating the boundary between laminar vs. turbulent flow of information through project organizations based on variables like the span of control of the organization, the degree of complexity of its tasks, and the level of centralization. This kind of Organizational Reynolds Number would then predict the point at which information flow in an organization becomes severely enough bottlenecked that exceptions would generate rework faster than it can be effectively completed (damped out, so that rework generates new exceptions and yet more rework). Exceeding such an "Organizational Reynolds Number" would cause hidden work and project duration both to increase dramatically. Michael Fyall, William Hewlett III, Per Bjornsson, and Tarmigan Casebolt all worked on this research at different times and began to home in on a set of variables that begin to predict when increasing any of these variables would make the information flow become "turbulent" – i.e., it would cause hidden work and project duration to increase exponentially rather than linearly (Levitt, Fyall, Bjornsson, Hewlett, & Casebolt, 2002). This is a truly exciting research challenge that begs for additional research.

Using VDT to Study Knowledge Flows

VDT was subsequently used to develop theory about knowledge flows through organizations by Nissen and Levitt (2004). Nissen and colleagues worked on several different aspects of knowledge flow including the impacts of discontinuous membership in project teams due to turnover or fragmentation across project phases (Ibrahim & Nissen, 2007). Following up on Nissen's work, Levine and Prietula (2011) studied circumstances under which knowledge transfer within organizations would be helpful vs. harmful to the organization.

Exploring Virtual Organizations and the Edge of Chaos

Rich Burton and his students and colleagues have used VDT extensively over the last decade to explore a number of organization theory questions. Timothy Carroll and Rich Burton conducted experiments to explore the "Edge of Chaos" – similar in some ways to the Organizational Reynolds Number work described above (Carroll & Burton, 2000). Zse-Zse Wong and Rich Burton (2000) used VDT simulations of different aspects of virtual organizations – project organizations whose participants were separated by geography and other kinds of distance – to develop propositions about their performance in different contexts. Jensen, Håkonsson, Burton, and Obel (2010) have further elaborated this

---

[5] The Reynolds Number is a dimensionless number that demarcates the boundary between laminar and turbulent flow of fluids. For fluid flowing through a pipe, when the Reynolds Number is below 2300, eddies that are created in the fluid get damped out by its viscosity. For Reynolds Numbers above 4000, eddies begin to generate secondary eddies faster than they can be damped out and the flow becomes turbulent. When the flow becomes turbulent, the pressure loss from fluid flowing through the pipe begins to increase with the square of the fluid's velocity rather than linearly with its velocity. In between these two values, the flow is "transitional" and can be either laminar or turbulent.

research. Kim and Burton (2002) used VDT simulations to study how task uncertainty and decentralization affect project team performance. And Burton and Obel (2011) show how VDT simulations can be triangulated against other simulations and empirical data to extend and refine organization theory. The citations over time for the experiments described above show that publications describing research using agent-based modeling tools like VDT to develop and extend organizational theory have moved from specialized journals focused on computational simulation to mainstream organization theory journals in the last few years.

EXTENSIONS TO THE ORIGINAL VDT MODEL

Since the mid-1990s, Stanford researchers have extended the representation and reasoning in VDT step-by-step, to address the modeling requirements of less routine work performed by increasingly flexible and dynamic organizations – non-routine product development, service and maintenance work (including healthcare delivery), and highly non-routine work performed in communities of practice – but still assuming negligible institutional work. Starting in 2002, we extended VDT to model multicultural project teams engaged in global projects to develop civil infrastructure involving firms from multiple national institutional backgrounds, for which institutional costs can become highly significant. Also, VDT was extended to model whole enterprises as Project Organization and Workflow for Enterprise Research ("POW-ER") to model highly non-routine work in extremely decentralized "Power to the Edge" organizations (Alberts & Hayes, 2003). This section elaborates the evolution of VDT over the past 20 years, its current status, and ongoing research in this area.

In selecting the kinds of organizations that VDT would initially model, we picked project teams performing routine design or product development work. For this class of organizations, all work is knowledge work so that we could fruitfully use an information-processing abstraction (Galbraith, 1974) of the work. For routine product development, goals and means are both clear and relatively uncontested, so that we could finesse many of the most difficult "organizational chemistry" and "organizational biology" modeling challenges inherent in the kinds of organizations that sociologists have often studied at the enterprise level – e.g., mental health, educational, and governmental organizations. Our intention from the outset was to start with "organizational information flow physics" and then progressively add elements of "organizational chemistry" and "organizational biology" to the modeling framework to extend its applicability to less routine tasks and more dynamic organizations. We have executed several steps of this research vision over the past two decades. Completed and ongoing versions of VDT that progressively addressed additional aspects of task and organizational complexity are shown in Figure 7.

Key Limitations of VDT2/SimVision

The Cohen (1992) and Christiansen (1993) VDT-1,2 framework has been fully validated through all of the steps shown in Figure 6. VDT-2 generates reliable predictions about 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 actors in the static organization; (3) exceptions to tasks are resolved through the hierarchy and generate extra work volume for the predefined tasks to be carried out by the pre-assigned actors; and (4) actors are assumed to have congruent goals, values, and cultural norms. These conditions fit many kinds of design and product development work. VDT-2 was commercialized as SimVision™ by Vité Corporation through Stanford's Office of Technology Licensing, and it is in use by companies in a variety of industries and governmental organizations including Procter & Gamble, Walt Disney, the US Navy, NASA, and The European Bank for Redevelopment and Construction.

Modeling Moderate Levels of Goal Incongruency

VDT-3 (Thomsen, 1997) extended the range of work processes that could 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. Actors can have the same set of goals, but incongruent goal preferences (i.e., a moderate degree of goal incongruency), causing them to disagree about how best to execute tasks in the project plan. Following concepts from economic "Agency Theory", goal incongruency levels between pairs of actors affect both their vertical and horizontal communication patterns.

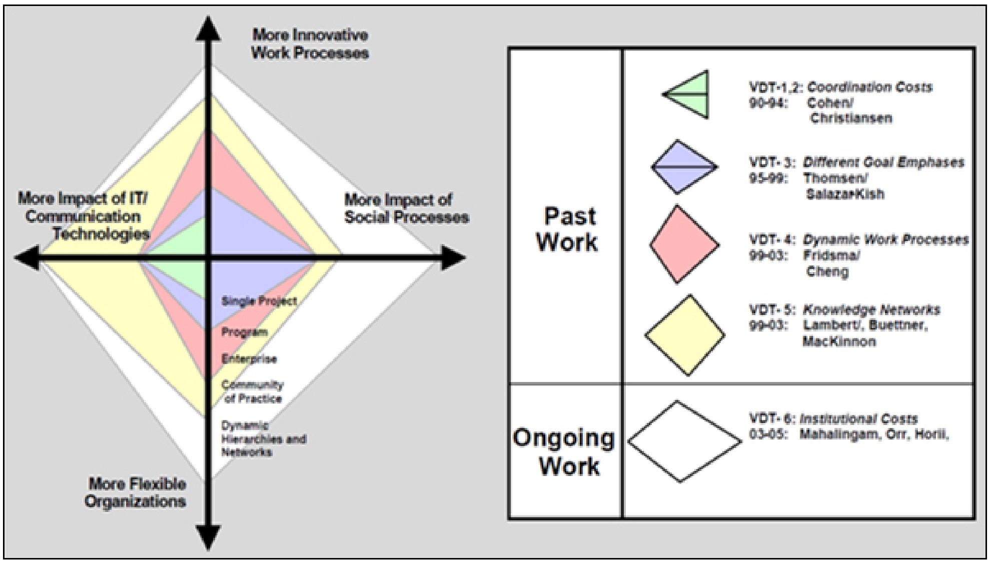

Fig. 7. VDT Research Trajectory

The range of work processes and organizations to which VDT can be applied were expanded step by step: VDT-1,2 for relatively routine, fast-paced project work executed by organizations with hierarchical exception processing, a predetermined and static structure and task assignments, but no significant institutional differences; to VDT 3 for less routine projects where goals of team members might be incongruent; to VDT-4 for non-routine "diagnose and repair" work (e.g., health care delivery or equipment maintenance) executed by more dynamic and adaptable organizations; to VDT-5 in which exceptions can be resolved through team members' knowledge networks rather than just via their supervisors in the hierarchy; to VDT-6 for global projects in which the costs of institutional exceptions arising from the differences in national institutions among team members become significant.

Modeling Less Routine Work Processes: Diagnosis and Repair

A subsequent NSF grant focused on extending the applicability of VDT beyond its previous limits on work-process routineness and static organizational structure. Douglas Fridsma developed VDT-4 to model complex and non-routine health care delivery tasks such as bone marrow transplants and similar complex, multi-specialty, medical protocols. In these work settings, diagnosis tasks indicate needed therapeutic tasks; any unplanned side effects that arise during diagnosis or therapy must be diagnosed and treated contingently. To model the indeterminacy inherent in these kinds of work processes, we had to relax the VDT-1,2,3 constraint that all tasks, actors, and assignments be rigidly pre-specified and remain static. This required several extensions to the VDT-3 framework.

Fridsma (2003) extended the information-processing micro-theory in VDT-3 to include a variety of more complex exceptions that can cause tasks to be added, re-sequenced, deleted, or reassigned, and actors to be dynamically added to the organization and assigned tasks as needed. This extended framework was implemented and internally validated on *toy problems* (see Figure 6). Carol Cheng Cain (Cheng, Cain, & Levitt, 2001) extended Fridsma's work to model context-dependent decision-making —e.g., medical decision-making in intensive care units where organization structure (e.g., level of centralization of decision-making) and staffing (by experienced medical practitioners vs. interns or residents) both change as a function of time of day or day of week— and she *retrospectively validated* VDT-4 predictions against empirical data in several clinical settings (Cheng Cain, 2003).

Modeling Flexible Exception Handling and Knowledge Sharing: "Communities of Practice"

A longer-range goal of our work was to begin modeling even more flexible organizations – dynamically shifting "communities of practice" in which actors can resolve exceptions by communicating not just up the hierarchy, but with anyone from their "knowledge network," either inside or outside their own project organization. Software development teams and some consulting organizations currently approximate this organizational form. Theories based on concepts such as public goods, homophily, or reciprocity can be used to describe how these links form and persist or dissolve in face-to-face working conditions, or in cyberspace for non-co-located teams. We received a NSF Knowledge and Distributed Intelligence (KDI) research grant to work with colleagues from USC, Carnegie Mellon, and the University of Illinois in this exciting new area, and we made significant progress in implementing these extensions. VDT-5, which included these extensions, was reprogrammed and released as **P**roject, **O**rganization and **W**orkflow-**E**xtended **R**esearch (POW-ER) (Ramsey & Levitt, 2005), and has since been used by the US Navy, the US Air Force Research Laboratory, and other governmental organizations.

Modeling Effects of Institutional Differences on Project Team Behavior and Outcomes

Research by Geert Hofstede (1997) and his colleagues provides one clear point of departure for modeling how differences in values and cultural norms can affect the behavior of participants in project teams. Hofstede identified five dimensions of culture that vary systematically between workers from different countries, and which affect individual and team behaviors in global, knowledge-intensive, dynamic, global projects. Hofstede collected large data sets based on IBM employees in more than 50 countries indicating that differences along one or more of these cultural dimensions lead to predictable kinds of misunderstandings, conflict, and loss of motivation in global work teams. This work was subsequently replicated, updated and extended by House, Hanges, Javidan, Dorfman, and Gupta (2004).

Drawing on Hofstede's work and on the results of a series of workshops conducted with Professor Douglass North (a Nobel Laureate in institutional economics at Stanford's Hoover Institute) and Professor Merlin Donald (an eminent Canadian cognitive psychologist) at the Institute for International Studies at Stanford, we developed a set of initial hypotheses about how to model the emergence of "institutional exceptions" and their information-processing costs in global projects within VDT. Scott's (2008) theory of institutions provides a more inclusive conception than Hofstede's limited view of culture as consisting of values and beliefs to explain how sets of mental schemata and individual, group, and legal ideations, norms, and laws drive behavior deemed to be appropriate for persons in different social groups. The doctoral research of Mahalingam (2005) and Orr (2005) found that viewing national differences in terms of institutional differences was far more productive in understanding and predicting cross-national institutional exceptions in projects than viewing them solely through the lens of the Hofstede/House ideas and values constructs.

Our approach was to model institutional work in the same way that we modeled coordination work – i.e., as additional quantities of information to be processed by actors in a project team. Figure 8 shows conceptually how we overlaid institutional work on the production work and coordination work that we had modeled to date. However, in addition to increasing the amount of information to be processed, institutional exceptions may also have the side effect of undermining the motivation of actors who find themselves engaged in continual misunderstandings, conflict, and even sabotage by project team members whose goals, beliefs and values, cultural norms, and legal/regulative systems are significantly different than their own.

Horii (2005) designed and conducted a set of computational experiments in which he modeled US and Japanese institutions (practices and values) and simulated the performance of joint venture teams consisting of US and/or Japanese managers and workers in US- vs. Japanese-style project organizations working on projects with different levels of complexity. His path-breaking work won the best-paper award at CASOS 2005. This line of work has continued since 2005 at the Collaboratory for Research on Global Projects (Scott, Levitt, & Orr, 2011). (See also < http://crgp.stanford.edu >.)

Managers of global projects contending with significant institutional differences need to be realistic about the additional "institutional work" that will be incurred in proceeding with their projects. Forewarned with this kind of prediction, they can set more realistic goals and begin to initiate effective interventions with a clear notion of how long they will take to implement. Additional validation and calibration of Horii's pioneering work will be required for them to do this.

Exploring Fully Automated Organization Design: Developing A Postprocessor for VDT

Organizational design is a complex global and local optimization problem involving continuous and discrete variables. For example, an organizational designer must size functional capabilities, assign staff to tasks, and set communication and control policies. VDT is an analysis tool that can predict schedule cost and process quality performance for a baseline case of an organization and work process, and help to isolate the most severe risks in these three areas. However, VDT cannot suggest how to intervene most productively to change the work process or organization, in order to mitigate any risks that have been identified. The user has to experiment with alternative cases to find better solutions. Searching the solution space manually to find good cases that address schedule, quality, or cost risks for a baseline case is thus a challenging task. It relies on the expertise of the human user and offers no guarantee of optimality or even near-optimality. Because the VDT solution space is so large, and the interaction between its variables is subtle and sometimes counterintuitive, even expert users can fail to discover many potentially superior solutions.

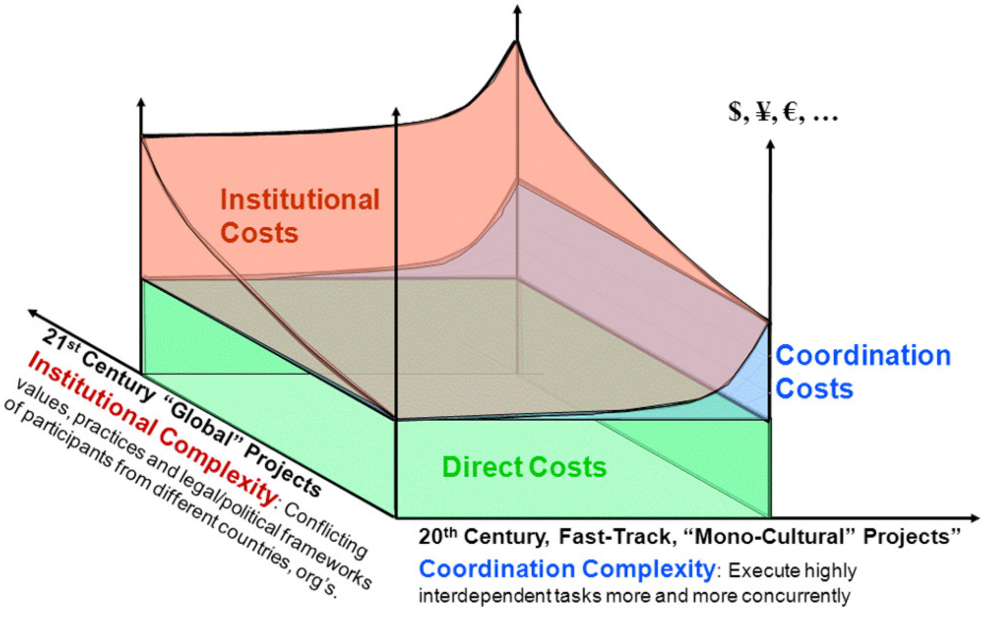

Fig. 8. Costs Arising from Three Kinds of Project Work

Direct costs for projects arise from the cost of assigned actors performing their direct tasks. Additional project costs arise from two kinds of "hidden work": (1) "Coordination Costs" arise from "supervision" – the need for managers to process technical exceptions, and "coordination" – the need for workers and their managers to coordinate interdependencies in highly concurrent project work, and the resulting rework when coordination breaks down; and (2) "Institutional Costs" arise from the need to handle "institutional exceptions" – misunderstandings and conflicts resulting from differences in the national institutions (Scott, 2008) of project team members from different countries, professions, or industry sectors.

During the 1990s, researchers began combining AI and OR techniques to solve several similarly complex kinds of optimization problems (Hooker, 2002). Working in collaboration with Professor John Koza, a pioneer in the development of Genetic Programming, Bijan KHosraviani (KHosraviani & Levitt, 2004; KHosraviani, Levitt, & Koza, 2004) developed a system based on Genetic Programming that was able to evolve VDT models that met a required set of scope, schedule, and cost objectives for a benchmark problem more optimally than multiple teams of human users had been able to do over almost a decade.

Genetic Programming (GP), applied to VDT, attempts to evolve multiple good solutions for a problem via a computational approach that mimics Darwinian evolution of species. In the case of VDT models, GP requires that the user create a "fitness function" that specifies the relative weight to be given to each early completion, low cost, and high quality, as well as to specify any constraints such as the latest possible completion time of the project or maximum number of additional FTEs that could be added to positions. An initial generation of solutions consisting of about 20 different VDT model cases is created as a starting point for the GP. VDT first simulates all of the solution candidates in the initial generation to predict their outcomes. Then the GP evaluates each case's fitness for survival and reproduction as defined by the fitness function, using the outcome predictions for duration, cost, quality, etc. that have been generated by the VDT simulations for the cases in that generation. The cases evaluated as being the fittest by this fitness function preferentially get to propagate themselves to the next generation in one of three ways: they "procreate" – i.e., they exchange genes by combining attributes of the case from a pair of relatively fit "parent" cases into a "child" solution in the next generation; they "mutate" – i.e., one or more randomly selected attributes of a case in a given generation are randomly assigned new values in the next generation; or they can "replicate," in which a relatively fit case is reproduced identically in the next generation so it can continue to pass on its good fitness attributes to future offspring cases. This computational analogy to "evolution of the fittest" proceeds through multiple generations until some cases in the latest generation reach acceptable fitness values.

KHosraviani developed an ingenious dimensional extension to traditional GP, inspired by Professor John Koza's previous work on using GP to "evolve" circuit designs from electronic components (Koza et al., 1996, 1999) akin to evolving multicellular creatures from single cell organisms in a primeval ooze. KHosraviani was then able to apply GP to this multidimensional optimization problem involving both numerical and non-numerical parameters. His GP algorithm was then able to evolve multiple "fit" solutions that surpassed the performance of the best solutions previously identified by multiple student teams in just 20–30 generations. KHosraviani's work was awarded a Silver Medal at the *Genetic and Evolutionary Computation* Conference (GECCO) in 2004.

GP is a computationally intensive process; it required a whole room full of computers linked together as a parallel processor at the time KHosraviani carried out his research. Today GP computations can be carried out on multiple servers "in the cloud."

Modeling Radically Decentralized "Power to the Edge" Organizations

The VDT research has continued since 2005 to develop an extension of VDT called Process, Organization, Work for Edge Research (POW-ER) that could be used to model some of the most decentralized and flexible organizations existing anywhere – so-called "Power to the Edge" organizations such as the US Special Forces team that tracked down and killed Osama bin Laden in 2011 (Alberts & Hayes, 2003) or "Project Management 2.0" organizations (Levitt, 2011) that are increasingly being used to implement "agile software development." POW-ER has now evolved through multiple versions. At the beginning of 2012, Version 3.8 incorporates the ability to model: institutional differences between participants from different nationalities (Horii et al., 2005); learning and forgetting of skills by project team members over the course of an extended project (MacKinnon, 2007); the development of trust between members of a project team who may or may not be co-located (Zolin et al., 2004); and flexible knowledge sharing through networks of human experts and computational support tools such as databases, expert systems, and other computer knowledge archives (Buettner, 2008).

In collaboration with Northrop Grumman Information Technology's Enterprise Applications Group and the US Air Force Research Laboratory we developed an extension of POW-ER to model command-and-control work and other kinds of monitoring and control workflow where predefined sequences of tasks are initiated stochastically by the arrival of intelligence, sensor, or other information, rather than being initiated by the completion of specified predecessor tasks, as in all the previous versions of VDT and POW-ER. We began validating Project Organization and Workflow-Information Driven (**POW-ID**) in the latter part of 2009 (Levitt, Chachere, & Ramsey, 2010).

This overview of the 20-year VDT research program has attempted to explain how a team of researchers was able to begin modeling organizations executing well-specified, complex, but semi-routine project tasks completed by team members with shared goals and institutions, and then to extend the representation and reasoning of the initial theory and tools progressively to address more flexible tasks, more heterogeneous project team membership, and finally more dynamic and decentralized organization structures, as shown in Figure 7. In Hemingway's words, it has been a "movable feast" to participate in this scientific exercise with a remarkable team of faculty and student scholars and collaborators from industry and government.

SUMMARY

This section summarizes where VDT came from, where it has been, its present status, and what might lie ahead for organizational researchers interested in this kind of agent-based simulation.

As we explained in the introduction, VDT arose from the need of managers like Art Smith, facing stringent economic and strategic pressures to execute their large and complex projects more rapidly and concurrently, to find ways to predict the outcomes of proposed organizational cases for their projects and design more effective organizations. Many thousands of projects are planned and executed each year in industries ranging from construction through pharmaceuticals, biotechnology, medical device development, consumer products, computers, software, and other sectors, for which scope is relatively fixed; the structure of tasks, positions, and task assignments are unlikely to change materially over the project duration; and exceptions are processed through one or more hierarchical channels. For this class of projects, VDT-2 has progressed through all the stages of validation in Figure 7 and its commercial descendent, SimVision™, is now routinely being used to support organization design on some of the world's largest projects.

The subsequent versions of VDT, POW-ER, and POW-ID described in the previous section have demonstrated great creativity by multiple PhD researchers in their conceptualization and implementation, and a limited capability to model and simulate more dynamic organizations composed of workers with less homogeneous backgrounds executing less well-structured tasks. However, none of these extensions has been validated extensively enough to support its routine use by practitioners by the end of 2011.

This is not entirely surprising. As stated earlier, semi-routine project organizations lie in the "easy corner" of the space of all organizations, and modeling organizational physics is much easier than modeling organizational chemistry or biology. The frontier of research in the latter two areas is still bounded by top-down rule-based diagnosis of the degree of internal and external fit between attributes of an enterprise's macro-organization structure and its environmental and managerial context, as exemplified by Burton and Obel's (2004) path-breaking Organizational Consultant integration of the contingency theory literature implemented in a book and a software package (OrgCon), and Shenhar's (2001) contingent propositions for designing project organizations and work processes. Looking forward, the article concludes with a set of challenges for researchers interested in advancing the frontier of VDT's model-based style of organization design beyond semi-routine project organizations to help managers like Art Smith design organizations for their increasingly globally networked and fast-changing 21st century projects.

Challenges for Future Research on Organization Design

This section sets out some near-term challenges for future research on model-based organization design that could build on the work described in this article to extend the range of applicability of organizational design theories, methods and tools.

Validating VDT-3 and Subsequent Versions of the VDT and POWER Software

Replication is one of the key means of testing and advancing scientific knowledge in all fields. Replication of early experiments on some of the extensions to VDT-2 described above, and resulting modification and calibration of the representation and reasoning in these simulation modeling tools, can begin to develop sufficient confidence in the predictions of these models of more flexible organizations and dynamic work environments for them to become useful for organization design in settings like healthcare, equipment maintenance, command-and-control organizations, and agile software development.[6]

Modeling Globally Networked Organizational Forms

The world of work and organizations is increasingly global. Moreover, as predicted by Malone, Yates, and Benjamin (1987), computers have driven transaction costs for outsourcing work in many situations toward zero so that today's organizations increasingly deliver their projects using far-flung networks of supply-chain partners rather than just their own direct employees. Agent-based modeling seems ideally suited for modeling the behavior of, and interactions between, global supply-chain partners such as can be found in construction, automobiles, mobile telephones, and many other kinds of mature products assembled from relatively standardized components. This represents an exciting area of near-term application for agent-based simulation technology (Chinowsky & Taylor, 2012). Secondly, networked organizations in mature industries face significant challenges when attempting to innovate systemically rather than at the module level (Sheffer, 2011). Again, agent-based models of project networks can shed further light on this important subject.

Dynamically Predicting and Controlling Project Organizations

Autopilots used to help pilots or captains guide and control airplanes or ships combine real-time data from a variety of sensors and other data sources about the airplane's internal operation and external variables (e.g., current engine and control surface settings, and en route traffic congestion or meteorological conditions) with the ability to predict the impact of changes in engine power, control surface orientation, etc. on the vehicle's trajectory, arrival time, fuel supply, etc., and to issue alerts to the pilots and or ground controllers when out-of-bounds conditions arise. Similarly, it would be worthwhile attempting to link tools like VDT (or, more likely, its commercial SimVision implementation) to the parent organization's "sensor network" and data – its IT systems for enterprise resources planning, customer relationship management, human resources, and the like – to help managers control their organizations dynamically in real time in accordance with both the organization's top-level strategic objectives and each project's objectives and constraints along with its actual progress to date in meeting those objectives and constraints.

Nissen and Burton (2011) have developed the concept of "dynamic fit" using control of the trajectory and orientation of an airplane as an analogy. They use the notion of "opportunity costs" as a kind of overarching fitness function for operationalizing organizational tradeoffs over time. Future versions of VDT could incorporate this notion in guiding managers' interventions toward more optimal organizational configurations.

---

[6] The author will gladly make current versions of the POWER software, implemented in the Python language, available to researchers interested in pursuing ongoing validation and extension of these agent-based modeling and simulation frameworks.

Developing Next Generation Simulation Models

In 1988, SmallTalk (Goldberg & Robson, 1983) and IntelliCorp's Knowledge Engineering Environment (KEE), which was implemented in LISP, were just about the only object-oriented computing languages available to our team, and the only object-oriented simulation language that could reason about non-numerical variables was IntelliCorp's KEE-SimKit™. KEE-SimKit provided us with a powerful prototyping language for Cohen's (1992) prototype of VDT-1, but it ran only on expensive and custom LISP-processing hardware from Xerox or Symbolics, and the simulations executed painfully slowly. This was a problem even for researchers, because the stochastic nature of VDT required us to run at least 100 simulations of each model case and develop average and standard deviation measures to interpret the results with any statistical reliability. When SimVision was commercialized in 1996, it was developed in C++, the object-oriented language based on C that has become widely used since the mid-1990s. This required the agent-based simulation functionality to be developed essentially from scratch; the advantage was that simulations implemented and compiled in C++ executed rapidly enough to be useful not only to researchers but also to managers.

If the VDT team were starting work today, we would be faced with a plethora of object-oriented programming environments that can be executed rapidly on desktop, laptop or "in-the-cloud" computers, and even multiple agent-based simulation environments such as the Santa Fe Institute's SWARM language for linked, multilevel, agent-based simulations (Minar, Burkhart, Langton, & Askenazi, 1996). The graphical tools for building model canvases and displaying simulation outputs have also evolved dramatically. Early versions of SimVision used Microsoft's Visio™ for this. Later versions deployed a custom-developed user interface built on graphical libraries from open-source or commercial developers. Researchers interested in developing models of supply-chain networks (Chinowsky & Taylor, 2012), knowledge networks, or other networks can similarly access powerful off-the-shelf social network modeling, analysis, and visualization tools such as UCINET (Borgatti, Everett, & Freeman, 2002). So progress in this field has the potential to accelerate dramatically.

CONCLUSION

As described above, the "information flow physics" of project organizations are now relatively well understood and modeled. The author's hope and strongly held belief is that – like their natural science counterparts – "organizational chemistry" (goal conflict, institutional differences, and the like) and "organizational biology" (individual learning, organizational learning, evolution and regeneration of networks of organizations) will eventually yield to robust and accurate enough agent-based modeling, analysis, and validation that simulation of these phenomena will become useful to managers like Art Smith in designing their globally networked 21st-century project organizations. There is much exciting work to be done!

REFERENCES

Alberts D, Hayes R. 2003. *Power to the Edge: Command… Control… in the Information Age*. Center for Advanced Concepts and Technology, Command and Control Research Program, US Department of Defense. http://www.dodccrp.org/files/Alberts_Power.pdf

Programming to Scheduling Problems. Kluwer Academic Publishers, Norwell, MA.

Borgatti SP, Everett MG, Freeman LC. 2002. *UCINET for Windows: Software for Social Network Analysis*. Analytic Technologies, Harvard, MA.

Buettner RR. 2008. The impact of communal knowledge mechanisms on project work (Doctoral dissertation, Department of Civil and Environmental Engineering, Stanford University.)

Burton RM, Obel B. 1995. The validity of computational models in organization science: from model realism to purpose of the model. *Computational and Mathematical Organization Theory* 1(1): 57–71.

Burton RM, Obel B. 2004. *Strategic Organizational Diagnosis and Design: The Dynamics of Fit, Third edition, (with OrgConSoftware)*. Kluwer Academic Publishers, Boston, MA.

Burton RM, Obel B. 2011. What-Is, what-might-be, what-should-be studies – and triangulation? *Organization Science* 22(5): 1195–1202.

Cardinal LB, Turner SF, Fern MJ, Burton RM. 2011. Organizing for product development across technological environments. *Organization Science* 22(4): 1000–1025.

Carroll T, Burton RM. 2000. Exploring 'complex' organizational designs. *Computational and Mathematical Organization Theory* 6(4): 319–337.

Carroll TN, Gormley TJ, Bilardo VJ, Burton RM, Woodman KL. 2006. Designing a new organization at NASA: an organization design process using simulation. *Organization Science – Special Issue on Organizational Design* 17(2): 202–214.

Carroll TN, Burton RM. 2012. A contingency approach to designing project organizations: theory and tools. *Engineering Project Organization Journal* 2(1-2): 5–14.

Cheng CHF, Levitt RE. 2001. Contextually changing behavior in medical organizations. *Proceedings of the 2001 Annual Symposium of the American Medical Informatics Association*, Washington, DC.

Cheng Cain CF. 2003. Representation and reasoning about contextually changing organizational behavior using simulation models of medical work (Doctoral Dissertation, Department of Biomedical Informatics, Stanford University.)

Chinowsky P, Taylor JE. 2012. Networks in engineering: an emerging approach to project organization studies. *Engineering Project Organization Journal* 2(1-2): 15–26.

Christiansen TR. 1993. Modeling efficiency and effectiveness of coordination in engineering design teams (Doctoral Dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Cohen GP. 1992. The Virtual Design Team: an information processing model of the design team management (Doctoral Dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Cohen KJ, Cyert RM. 1965. Simulation of organizational behavior. In J. G. March (Ed.), *Handbook of Organizations*. Rand McNally, Chicago, IL, 305–334.

Cohen MD, March JG, Olsen JP. 1972. A garbage can model of organizational choice. *Administrative Science Quarterly* 17 (1): 1–25.

Epstein JM, Axtell R. 1996. *Growing Artificial Societies: Social Science from the Bottom up*. Brookings Institution, Washington, DC.

Frisma D. 2003. Organizational simulation of medical work: an information-processing approach (Doctoral Dissertation, Department of Biomedical Informatics, Stanford University.)

Galbraith JR. 1974. Organizational design: an information processing view. *Interfaces* 4: 28–36.

Goldberg A, Robson D. 1983. *Smalltalk-80: The Language and its Implementation*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA.

Hofstede G. 1997. *Cultures and Organizations: Software of the Mind*. McGraw Hill, New York.

Hooker J. 2002. Logic, optimization, and constraint programming. *INFORMS Journal on Computing* 14(4): 295–321.

Horii T. 2005. Impact of Multiple Normative Systems on the Organizational Performance of International Joint Ventures (Doctoral Dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Horii T, Jin Y, Levitt RE. 2005. Modeling and analyzing cultural influences on project team performance. *Computational and Mathematical Organization Theory* 10 (4): 305–321.

House RJ, Hanges PJ, Javidan M, Dorfman PW, Gupta V. 2004. *Leadership and Organizations – the GLOBE study of 62 Societies*. Sage Publications, Inc.

Ibrahim R, Nissen ME. 2007. Discontinuity in organizations: developing a knowledge based organizational performance model for discontinuous membership. *International Journal of Knowledge Management* 3(1): 18–36.

Jensen KW, Håkonsson DD, Burton RM, Obel B. 2010. The effect of virtuality on the functioning of centralized versus decentralized structures – an information processing perspective. *Computational and Mathematical Organization Theory* 16(2): 144–170.

Jin, Y, Levitt RE. 1996. The Virtual Design Team: A Computational Model of Project Organizations. *Journal of Computational and Mathematical Organization Theory* 2 (3):

171–195.

KHosraviani B, Levitt RE. 2004. Organization design using genetic programming. Proceedings of North American Association for Computational Social and Organizational Science (NAACSOS) Conference, Pittsburgh, PA, June 27–29.

KHosraviani B, Levitt RE, Koza JR. 2004. Organization design optimization using genetic programming. In M. Keijzer (Ed.), *Late-Breaking Papers at the 2004 Genetic and Evolutionary Computation Conference (GECCO-2004)*. Seattle, WA International Society of Genetic and Evolutionary Computation.

Kim J, Burton RM. 2002. The effect of task uncertainty and decentralization on project team performance. *Computational and Mathematical Organization Theory* 8 (4): 365–384.

Klein R. 2000. *Scheduling of Resource-Constrained Projects*. Kluwer Academic Publishers, Norwell, MA.

Koza JR, Bennett FH III, Andre D, Keane MA, Brave S. 1996. *Genetic Programming III Videotape: Human-Competitive Machine Intelligence*. Morgan Kaufmann, San Francisco.

Koza JR, Bennett FH III, Andre D, Keane MA. 1999. *Genetic Programming III: Darwinian Invention and Problem Solving*. Morgan Kaufmann, San Francisco.

Kunz JC, Christiansen TR, Cohen GP, Jin Y, Levitt RE. 1998. The Virtual Design Team: a computational simulation model of project organizations. *Communications of the Association for Computing Machinery (CACM)* 41(11): 84–91.

Levine SS, Prietula MJ. 2011. How Knowledge Transfer Impacts Performance: a multi-level model of benefits and liabilities. Organization Science, *Articles in Advance*: 1-19.

Levitt RE, Cohen GP, Kunz JC, Nass CI, Christiansen T, Jin Y. 1994. The 'Virtual Design Team': simulating how organization structure and information processing tools affect team performance. In K. M. Carley and M. J. Prietula (Eds.), *Computational Organization Theory*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Levitt RE, Thomsen J, Christiansen TR, Kunz JC, Jin Y, Nass C. 1999. Simulating project work processes and organizations: toward a micro-contingency theory of organizational design. *Management Science* 45 (11): 1479–1495.

Levitt RE, Fyall M, Bjornsson P, Hewlett W III, Casebolt T. 2002. When information flow in project organizations becomes turbulent: toward an organizational Reynolds Number. *Proceedings of the Conference on Agent-Based-Modeling in the Social Sciences*, UCLA: 3–10.

Levitt RE, Chachere J, Ramsey M. 2010. Organizational research generator for simulation in the military. *Collaboratory for Research on Global Projects, Stanford University, Working Paper #0060*. http://crgp.stanford.edu/publications/working_papers/Chachere_ORGSIM_WP0060.pdf

Levitt RE. 2011. Toward project management 2.0. *Engineering Project Organization Journal* 1(3): 197–210.

Long CP, Burton RM, Cardinal LB. 2002. Three controls are better than one: a computational model of complex control systems. *Computational and Mathematical Organization Theory* 8(3): 197–220.

MacKinnon DJ. 2007. How individual skill growth and decay affect the performance of project organizations (Doctoral dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Mahalingam A. 2005. Understanding and mitigating institutional costs on global projects (Doctoral dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Malone TM, Yates J, Benjamin RI. 1987. Electronic markets and electronic hierarchies. *Communincations of the Association of Computing Machinery* 30 (6): 484–497.

March JG, Simon HA. 1958. *Organizations*. Wiley, New York.

Masuch M, LaPotin P. 1989. Beyond garbage cans: an AI model of organizational choice. *Administrative Science Quarterly*, 34 (1): 38–67.

Minar N, Burkhart R, Langton C, Askenazi M. 1996. The Swarm simulation system: a toolkit for building multi-agent simulations. Santa Fe Institute, Santa Fe, NM. www.swarm.org/images/b/bb/MinarEtAl96.pdf

Nissen ME, Levitt RE. 2004. Agent-based modeling of knowledge-flows: Illustration from the domain of information systems design. *Proceedings of Hawaii International Conference on System Sciences*, Waikoloa, HI.

Nissen M, Burton RM. 2011. Designing organizations for dynamic fit: system stability, maneuverability, and opportunity loss. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans* 41(3): 418–433.

North DC. 1990. *Institutions, Institutional Change, and Economic Performance*. Cambridge University Press, Cambridge, UK.

Orr RJ. 2005. Unforeseen conditions and costs on global projects: learning to cope with unfamiliar institutions, embeddedness and emergent uncertainty (Doctoral dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Ramsey M, Levitt RE. 2005. A computational framework for experimentation with edge organizations. *Proceedings of the International Command & Control Research Symposium*, McLean, Virginia.

Schrage M. 2000. *Serious Play: How the World's Best Companies Simulate to Innovate*. Harvard Business School Press, Boston, MA.

Scott WR. 2008. *Institutions and Organizations,* 3rd Ed. Sage Publications.

Scott WR, Levitt RE, Orr RJ. (Eds.) 2011. *Global Projects: Institutional and Political Challenges*. Cambridge University Press, Cambridge, UK.

Sheffer DA. 2011. Innovation in modular industries: implementing energy-efficient innovations in US buildings (Doctoral dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Shenhar A. 2001. One size does not fit all projects: exploring classical contingency domains. *Management Science* 47(3): 394–414.

Simon HA. 1947. A*dministrative Behavior: A Study of Decision-making Processes in Administrative Organization*. Macmillan, New York.

Steward DV. 1981. The design structure system: a method for managing the design of complex systems. *IEEE Transactions on Engineering Management* 78(3), 71–74.

Thompson JD. 1967. *Organizatons in Action*. McGraw-Hill, New York.

Thomsen J. 1998. The virtual team alliance (VTA): modeling the effects of goal incongruency in semi-routine, fast-paced project organizations (Doctoral dissertation, Department of Civil & Environmental Engineering, Stanford University.)

Thomsen J, Kwon Y, Kunz JC, Levitt RE. 1997. Simulating the effects of goal incongruency on project team performance. Fourth Congress on Computing in Civil Engineering, ASCE, Washington, DC, 643–650.

Thomsen J, Levitt RE, Kunz JC, Nass CI, Fridsma DB. 1999. A trajectory for validating computational emulation models of organizations. *Journal of Computational and Mathematical Organization Theory* 5(4): 385–401.

Wong S, Burton RM. 2000. Virtual teams: what are their characteristics and impact on team performance? *Computational and Mathematical Organization Theory* 6(4): 339–360.

Zolin R, Hinds PJ, Fruchter R, Levitt RE. 2004. Interpersonal trust in cross-functional, geographically distributed work: a longitudinal study. *Information and Organization* 14(1): 1–24.

RAYMOND E. LEVITT

Kumagai Professor of Engineering
Stanford University
E-mail: ray.levitt@stanford.edu