Modeling Effects of Organizational Structure and Communication Tools on Design Team Productivity

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This paper reports the initial development and testing of an AI symbolic model of some aspects of the behavior of an engineering design organization. The model explicitly represents concepts from organization theory, the social science discipline that describes the ways that differentiated groups communicate and function in integrated ways in a business organization. This paper discusses aspects of that theory and how we represented it in the model. The Virtual Design Team (VDT) model is a formal symbolic computational discrete event simulation model based on organization theory. It includes a high level of detail about tasks, actors and communications tools, describes static relationships among these entities, and uses simulation to predict their dynamic behavior and to predict project performance. Its behavior also compares well with observed behavior of two actual Civil Engineering design projects. The simulation model can be "run" relatively quickly. Thus, it can serve as a facility to formulate and test large numbers of precise conjectures regarding how changes in management structure or use of new communications tools will affect the organization's performance. Engineering disciplines have long had mathematical and, more recently, computational models in support of analysis and optimization of physical systems. This work shows that AI symbolic modeling can be used to express and to test social sciences models applied to real organizations. This work demonstrates the applicability of AI symbolic modeling techniques for making models that describe the detailed structure and predict the behavior of social theory and human organizations.

Introduction

This section introduces the organizational theory and our model of this theory. Following a case example, we elaborate the model design and then discuss methods and results.

Simon and March suggested an information processing perspective on organization behavior: organizations can and must arrange themselves to distribute decision making responsibility, share information required for decisions, and review and approve decisions [Simon, March]. In the tradition of model-based reasoning [Davis, Kunz], VDT explicitly represents the structure, intended function and actual behavior of organizational entities, including actors, tasks, projects, communication tools [Cohen]. Attributes of these entities typically have discrete qualitative values. For example, experience of an actor may be "high", "medium", "low"; the natural idiom of a task may be one or more of "words", "schematics", or "plans", etc.

Hierarchy is introduced into organizations with the intended function of identifying and resolving "exceptions" [Galbraith], situations in which the information required to complete a task is not available at the responsible node. Organizations allow lateral communication among peers to facilitate exception resolution with minimum communication. This Galbraith framework forms the basis for the VDT model; the model explicitly represents organizational entities, and it

reasons about the (stochastic) behavior of processing nodes, communications nodes and channels, and exception processing.

[Galbraith] theorized that the structure and behavior of its information processing nodes and communication channels will affect the performance of the organization. This "Contingency theory" provides the theoretical foundation of the VDT simulation. Galbraith describes contingency theory at the level of an actor and task: actor performance degrades (i.e., an "exception" arises) when an actor lacks some information required to complete a task. Although contingency theory assumes that actors are rational, we modeled the bounded rationality ideas of [March] and [Simon]. VDT allows availability of information and actor capability to limit task performance. Finally, Simon argues that decision-making is partially structured and partially random. To represent this partially random behavior, VDT is a stochastic discrete event simulation model.

Example Test Case

To verify that we represent and reason using organization theory effectively, we observed two civil engineering design projects and modeled one in detail. We compared theoretical predictions about organizational behavior with those of the design project manager and those of the simulation. The projects were relatively routine 3-year design and construction projects of $150M and $500M. These test cases are examples of real, routine engineering: needs of the project dictated project decision-making, not political needs of the organization or the client. The team understood engineering design issues well, so the organization did not need to respond to novel technical problems.

The complete model has over 100 attributes. Because of the size of the attribute space, validation of every possible combination of attribute values is impractical. We used a principled but limited factorial analysis to validate the system's internal consistency: for several sets of test cases, we selected two interacting attributes that Galbraith's model of Contingency theory predict will affect organizational performance: organizational structure and communications tools that can be used by actors. The simulation varies the allowed values of these selected attributes systematically in each test case. All other attribute values are set to a nominal value such as "medium".

Working with managers at a cooperating company to obtain realistic data about actors, tasks and tools, we simulated the organization performance for two choices of communications tools. In both cases, we did a 2 x 2 study considering change in information processing tools (first, introduction of voice mail, as shown in Figure 1, and second, video conferencing) and change between centralized and decentralized decision-making responsibility. In both cases, there was qualitative consistency between our predictions of project duration based on the Galbraith theory, the prediction of the on-site project manager, and the VDT simulation. The case studies of real organizations included about 90 high level activities and over 1,000,000 simulation events.

For example, one case (Case-1 in Figure 1) modeled a particular realistic design task and a baseline set of actor and communication tool capabilities. Actors had a set of communications tools including telephone, fax, voice mail, etc. The actors had decentralized control. In the simulation, computed project duration was 862 simulation units with a standard deviation of 8 units. This actual project duration lasted approximately 485 days, so the 862 simulation units corresponds to about 485 days for the assumptions used in this project. Case-2 held the task and actor parameters constant, but

Decision-Making	Information Processing Technologies: Voice mail	Information Processing Technologies: No Voice Mail
Distributed, Decentralized	1. (Baseline) [862, SD 8]	2. (Increased) [888, SD 1]
Hierarchical, Centralized	3. (Increased) [930, SD 10]	4. (Increased) [970, SD 16]

Figure 1. Qualitative change in simulated project performance in different organizational cases. Parenthesized remarks indicate the theoretically predicted change in project duration of Cases-2, 3 and 4 with respect to the baseline of Case-1. Bracketed numbers show number of simulation time units required to perform the project in each case, followed by the standard deviation on those estimates. We conclude that VDT can consistently represent the information processing patterns of engineering organizations doing routine tasks.

actors could not use voice mail as allowed in Case-1. Theory predicts that the overall project duration in Case-2 should be marginally increased than Case-1, i.e., duration "(Increased)" in the table. Bracketed numbers show that simulated project duration was greater than in Case-1, as predicted.

The results are statistically significant, as suggested by the relatively small standard variations. Case-3 used the same task, tool and actor descriptions as in Case-1, except that actors had centralized decision-making control. In each of Cases 2-4, there was three-way consistency about change in duration with respect to Case-1 among predictions made by the project manager of the modeled project, our predictions based on theory, and the simulation results.

Formal Symbolic Model of Organizational Theory

The VDT model is an object-oriented symbolic model. The VDT model is formal in that it explicitly represents concepts from the theory of organizational behavior, e.g., actors, tasks, information processing nodes and channels, bounded rationality of actors, etc. The VDT model is symbolic in that it explicitly represents conceptual and actual entities (e.g., actors, tasks, etc.) as reified entities (called objects) with attributes and certain behaviors, rather than representing the model as equations or as data with summarizing regressions. In addition, the model simulates behavior of entities as they perform their intended functions, given a set of initial assumptions. It has independent variables whose qualitative values are varied systematically between case runs, parameters whose qualitative values are fixed for a set of cases, and output, i.e., project duration. Discrete events in the simulation mark the processing of information messages by actors and tools.

Task descriptions include the type of information to process (words, schematics, plans, etc.); task

predecessors and successors, based on [Thompson]; number of messages needed to complete the task; constraints on related tasks; complexity (high, medium or low); variability (high, medium or low); percentage completed; and budgeted duration. Actor descriptions include reporting structure, responsibilities, and communication pattern (either strictly hierarchical or using peer-to-peer contact). Additional actor attributes include the organizational location of other actors to whom they can send communications (vertical only or vertical and lateral); task experience, based on [Mintzberg] (high, medium or low); and types of messages they process most effectively (words, schematics, plans, etc.).

Actors include managers and different kinds of design teams such as the electrical, process, and engineering teams. Actors perform the following functions, all implemented as object-oriented methods attached to appropriate objects:

- *Select communications from an "in-tray".* As suggested by Simon, attention, or the information selection process, is a crucial feature of organizations, but he observes that selection is not strictly rational. VDT uses stochastic "attention rules," implemented as methods on actor objects, to select communications from the in-tray.
- *Process information.* Time to process a message depends (stochastically) on the task features, nominal duration, degree of variability, and the degree of the match between the attributes of an actor and a message.
- *Send communications to an "out-tray" for distribution.* Distribution may (stochastically) be by a tool that is suitable for the particular type of communication and the workload of related actors and tools. Actors have methods that assign a priority to outgoing messages, based on the priority of the task.
- *Generate activities to coordinate actors*, based on the need for exceptions to obtain or share additional information, as suggested by [Galbraith]; requirements for periodic or percentage-completion updates; and requirement for milestone review dictated by project policy. VDT generates exceptions based on actor capability and degree of match between actor capability to process a particular message and the message attributes.

Actors can perform one task at a time, a sequential processing limitation suggested by [March] and [Mintzberg]. However, tasks can be interrupted by higher priority tasks.

Information processing tools, such as meetings, voice mail and video conferencing, have attributes including synchronicity (synchronous, partial, asynchronous); cost (low, medium, or high); proximity to user, capacity (volume of messages that can be transmitted concurrently); idioms supported (words, schematics, etc.).

The model entities have stochastic behavior. As discussed above, the values of most actor and tool attributes can either be one of a set of discrete alternatives or a number from a range for an attribute such as task duration. Each time the simulator makes a stochastic decision, the value used in the processing of a particular message is chosen stochastically by an algorithm that samples values from an alternative set according to a probability distribution set by the developer. Discrete attribute alternatives, numeric ranges and probability distributions were derived from field observations of engineering design teams.

The simulation can record and the investigator can inspect the status of every object throughout the project. We chose to look at one dependent output variable, the overall time for all project teams in the aggregate to

complete a project. Since many activities are performed concurrently, this overall duration corresponds to a critical path duration and not to the sum of durations for all subtasks needed to complete the project. The latter is also available from the simulation. It gives a measure of the total project cost.

Discussion

AI symbolic model-based reasoning (MBR) techniques were originally developed to model engineering theories and artifacts. The VDT project works in that tradition to model organizational theory and human organizations as artifacts. VDT provides a computational implementation of organization theories, thereby adding an internal consistency and testability to those social science theories. We can now begin to contrast symbolic modeling of physical and social artifacts.

Building any symbolic model requires developing deep understanding of the theories and artifacts to be modeled, developing appropriate abstractions, and representing those abstractions effectively. For example, physical system entities are often discrete, such as resistors and doors. Parameters of physical systems are often relatively clear and either measurable or computable, such as dimensions, voltages, and heat capacity. States frequently are used to characterize physical systems. Definitions of states are usually relatively clear in principle, although their precise specification may be vague (or even "fuzzy"). In contrast, we find that the theories and artifacts of organizations are significantly more abstract than we have found in building symbolic models of physical artifacts. For example, "organization" is a more abstract concept than "wall" or even "structural support system". We have tried to base the VDT model on rich and detailed understanding of organizational theory. We motivated the choice of concepts to reify as objects largely based on our synthesis of organization theory. Sometimes the theory also motivated the details of our choice of attributes and relationships of conceptual entities, e.g., theory describes activities quite precisely as having start time, duration, responsible actor, etc. Frequently, however, we found little theory to suggest entity attributes. A notable VDT example concerns communications tools: theory says that they are important, but there is little theory to describe their properties. In addition to such obvious properties as speed, availability and cost, we invented abstract properties including synchronicity and natural idiom a tool can transmit. These new abstract properties were very useful in VDT, and we will describe them in the organization literature.

In engineering applications of MBR, initial test cases have been conceived that usually are simple enough to be analyzed with confidence by a careful investigator. Investigators often can, at least in principle, perform definitive tests to demonstrate that a symbolic model describes and predicts the structure and behavior of an actual physical artifact operating in some conditions, if not all. Since social systems cannot be observed or manipulated in detail in their natural states, "gold standard" testability is usually not possible for models of social systems, even in principle. Nonetheless, we gained confidence in the validity of our models because of the consistency of the results of our three-way comparison of prediction by experts using theory, asking opinions of managers of the groups that we modeled, and VDT descriptions and predictions based on simulation.

In this social science application of MBR symbolic modeling, we have needed to synthesize complicated, incomplete and partially inconsistent theory. Our other engineering work required some theory synthesis, but much less. We have found the use of

object-oriented representation to be effective for building abstractions of both engineering and social science theories.

Classic organization theory is purely descriptive (or prescriptive): it is not operationalized. This paper summarizes how we operationalized the theory and introduces how we made major extensions to it to build the formal symbolic model. The operationalized model gives us the ability to test the descriptions and predictions of the formal theory much more precisely and rigorously than has been allowed by the descriptive theory. Its formal basis gives the VDT model a legitimacy that we could not claim if we had simply built the model based on our experience or intuition. By building a model based on an interpretation of formal theory that is largely symbolic and qualitative, we are working in a symbolic modeling tradition that has been used successfully in other areas of engineering [Kunz].

Numerous investigators have worked in the general area of modeling organizational theory. The pioneering work of Masuch and LaPotin is a symbolic, rather than equation-based, simulation model of the commitment, cognitive capacity and structure of actors in an organization [Masuch]. They built on a limited rationality theory which did not emphasize information processing, attention and exceptions, as does Galbraith's. They contributed the limited blocking test design which we used, but they did not report comparisons of the predictions of their model with real organizations. [Malone] discusses the use of information technology in organizations and its interaction with organizational structure. Carley et al [Carley] discuss the use of the SOAR model of a small organization in which intelligent agents communicate and cooperate to accomplish a simple task. Their research focuses on the information processing capabilities of processing agents and organizational structures.

The VDT model represents and reasons in great detail about routine organizational issues such as degree of lateral coordination among project team members, meeting frequency, tools used for communication among team members, and number of people attending meetings. The object-oriented VDT model is based explicitly on the information processing theories of Galbraith, Simon, March and others. VDT provides a language in which this theory has been expressed in a symbolic computational model. For multi-disciplinary teams doing routine designs in the Architecture-Engineering-Construction industry, the VDT validation indicates that the computational expression of the language effectively describes basic patterns of information processing and their effects on one measure of project outcome.

References

Carley, K., Kjaer-Hansen, J., Prietula, M., Newell, A., "Plural-Soar: A Prolegomenon to Artificial Agents and Organizational Behavior", Technical Report, Department of Social and Decision Sciences, Carnegie-Mellon University, 1990.

Cohen, G.P., *The Virtual Design Team: An Information Processing Model of Design Team Management*, Ph.D. thesis, Department of Civil Engineering, Stanford University, 1992.

Davis, R., "Diagnostic Reasoning Based on Structure and Behavior," *Artificial Intelligence*, 24 (1984), 347-410.

Galbraith, J., *Organization Design*, Addison-Wesley, Reading, MA, 1977.

Kunz, J.C., Stelzner, M.C., and Williams, M. D., "From Classic Expert Systems to Models: Introduction to a

Methodology for Building Model-Based Systems," in G. Guida and C. Tasso (Editors), *Topics in Expert System Design*, North-Holland, Amsterdam, 1989, pp 87-110.

Levitt, R. E., G. P. Cohen, J. C. Kunz, C. I. Nass, T. Christiansen, Y. Jin, "The 'Virtual Design Team': Simulating How Organization Structure and Information Processing Tools Affect Team Performance," to appear in *Computational Organization Theory,* Kathleen Carley and Michael Prietula, Eds., Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1993.

Malone, Thomas W., and Crowston, K., *What is Coordination Theory and How Can It Help Design Cooperative Work Systems*, MIT, Sloan School, Working Paper, No. 3183, 1990. (To appear in *Proceedings of the Conference on Computer Supported Cooperative Work*, Los Angeles, California, October, 1990.)

March, J.G., and Simon, H.A., *Organizations*, New York, Wiley, 1958.

Mausch, M., LaPotin, P., "Beyond Garbage Cans: An AI Model of Organizational Choice", *Administrative Science Quarterly,* 34, pp. 38-67, 1989.

Mintzberg, H., *The Nature of Managerial Work*, Harper & Row, New York, 1973.

Simon, H.A., *Administrative behavior: a study of decision-making processes in administrative organization*, New York: Free Press, 1976.

Thompson, J.D., *Organizations in Action,* McGraw-Hill, New York, 1967.

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