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ABSTRACT

This paper reports the initial results of a project to build and test a computer simulation model of information processing and communication in a multidisciplinary engineering design organization. The Virtual Design Team (VDT) is a computational discrete event simulation model based on qualitative reasoning concepts derived from artificial intelligence research. VDT explicitly incorporates information processing and communication models from organization theory that allow qualitative predictions of organizational performance. The inputs to VDT are: a description of the design task and the subtasks that comprise it, including sequential dependencies between subtasks; a description of the actors in the design team and of their organizational structure; and a listing of the communication tools (e.g., facsimile, voice mail, electronic mail, meetings) available to each actor. The output of VDT is a prediction of the time required to complete each subtask (a surrogate for total labor cost of design), and the time to complete the entire design project along the longest or "critical" path through subtasks. VDT's behavior has been validated extensively for internal consistency. Its behavior also compares well with theoretical predictions about, and the observed behavior of, a 120-person team engaged in the design of a large petrochemical refinery. The simulation model can serve as a facility to formulate and test specific conjectures regarding the qualitative effect on project cost and duration of changes in the organization structure of the team, or in the communications tools available to participants. Engineering disciplines have long had mathematical models and, more recently, numerical computational models, to support analysis and optimization of physical systems. This work provides initial evidence that symbolic computer modeling can be used to express and test social science theories applied to real world organizations and the communication tools that they employ.

Introduction

Design of artifacts to meet human needs—whether they be physical artifacts such as buildings, or social artifacts such as business organizations—is an ubiquitous human activity and can be broken down into the following generic steps:

1, *Requirements definition*—A set of functional, esthetic, and other objectives for the artifact are specified, along with cost, time, regulatory and other constraints; the required behavior of key subsystems and components can be derived from this set of objectives and constraints for the artifact;

2. *Synthesis* —A candidate design solution is synthesized, typically by selecting elements from sets of more or less standard primitive components or features, connecting them (to provide load paths, fluid flow channels, information communication channels, etc), and locating the elements in space;

3. *Analysis*—The behavior of each candidate solution is predicted by simulating the behavior of the system of connected primitive elements, using cognitive, physical, mathematical or computational models;

4. *Evaluation* —The behavior of each candidate solution's subsystems (at whatever level of detail is deemed necessary) is compared against the derived requirements for subsystem behaviors; and

5. *Acceptance or Recycling—Based on the evaluation of performance,* a candidate solution is accepted or the cycles back to synthesis, with changes guided by the latest evaluation results [Levitt 91].

For physical systems such as chemical plants or complex building structures, the behaviors of interest (e.g., reaction products or deflections) can often be predicted by solving sets of equations involving continuous numerical variables. Since the 1960s, the analysis phase of design for many kinds of physical artifacts has been revolutionized by the use of computational analysis tools which have greatly speeded up analysis, and have extended its range to situations where closed-form mathematical analysis was previously impossible.

In contrast, the use of computers to support analysis in the design of social artifacts has been very limited. Most organizational behaviors of interest to scientists or managers can only be represented as discrete, nominal or ordinal variables, leading to a mismatch between these theories and the continuous, quantitative models suited to traditional simulation techniques. However, during the 1980s, artificial intelligence (AI) researchers developed techniques for representing discrete, non-numerical variables, and for reasoning rigorously about relationships between them [Kunz 89]. These qualitative reasoning techniques provide researchers with a powerful new set of tools to begin developing computational models of problem domains that require qualitative reasoning with discrete, non-numerical variables [Clancey 89]. A number of engineering researchers have embraced AI techniques to begin formalizing other phases of design, in particular, *synthesis* of physical artifacts and assembly sequences to manufacture them [Coyne 90], [Levitt 90].

Although others have proposed the use of artificial intelligence modeling ideas to simulate micro-organizational behavior—e.g., [Masuch 89], [Bushnell 88], [CohenM 86], [Carley 90]—the Virtual Design Team is a pioneering effort to employ ideas from artificial intelligence for modeling the behavior of full scale organizations [CohenG 91,92]. Our long range goal is to develop robust computer simulation models of large-scale, concurrent engineering organizations in order to predict the impact of alternative organization structures and communication tools on the quality, cost and production time of their products. The VDT model described here is a first step toward that goal: Given a detailed descriptions of tasks, actors (individuals and groups), communication tools available to actors, the organizational structure, and an abstract definition of the product to be designed, the VDT predicts the duration of the design project. The present research treats the tasks, actors, and product as fixed and examines the impact of different tools and organizational structures on task and sub-task productivity. This approach is presented in Figure 1.

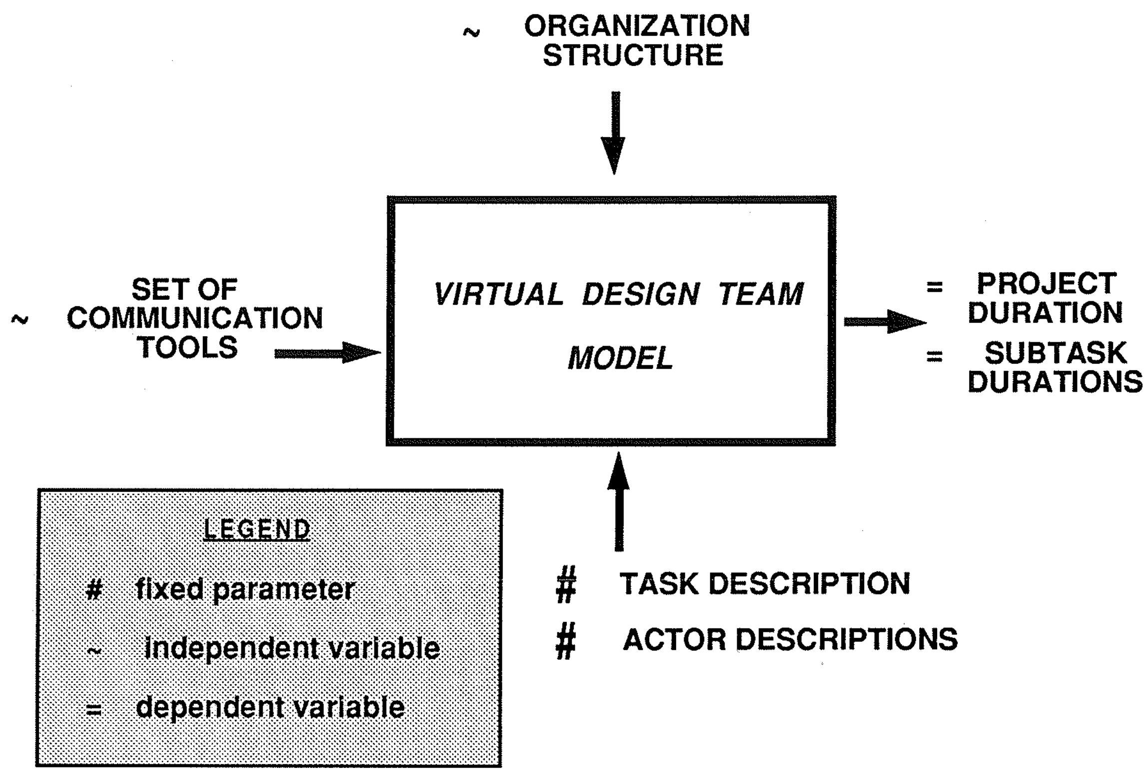

Figure 1. Inputs and outputs of VDT. The VDT model allows the user to specify the description of the tasks to be performed and the capabilities of organizational participants, termed "actors." The independent variables of the model include communication tools, used for sending messages between actors, and the "organization structure" of the team—i.e., the authority and responsibility of each actor, and the information processing relationships between actors. Model outputs include the durations of individual subtasks and the overall project duration.

To verify our representation and reasoning framework, we chose to test VDT by observing and modelling a large petrochemical design project. This project was selected as a test case because the decision-making structures and communication tools employed were selected by the managers, rather than being dictated by the parent organization or the client. In addition, the engineering design issues were well understood, without significant or novel technical problems.

The body of organization theory represented in VDT is reviewed next.

Organization Concepts Represented in VDT

The basic premise of the VDT model is that organizations are fundamentally information-processing structures—a view of organizations that dates back to Max Weber's work in the early 1900s, and that is elaborated in the work of March, Simon, and Galbraith [March 56], [Simon 76], [Galbraith 77]. In this view, an organization is an information-processing and communication system, structured to achieve a specific set of tasks, and comprised of limited information processors (individuals or sub-teams). These information processors send and receive messages along specific lines of communication (e.g., formal lines of authority) via communication tools with limited capacity (e.g., memos, voice mail, meetings, etc.). To capture these characteristics and constraints, the VDT employs explicit descriptions of tasks, communications, actors, tools, and structures. Thus, for example, each modelled manager has specific and limited (boundedly rational) information processing abilities; and managers send and receive messages to and from other actors along pre-specified communication channels, choosing from a limited set of communication tools. The view of organizations that we have implemented is presented in Figure 2.

Task

Our goal is to analyze engineering design teams carrying out routine designs. We, therefore, view the task of the design team as the completion of a set of pre-determined milestones. These milestones consist of the design, review, and approval of a series of components or sub-systems of the artifact to be designed. For instance, in the case of a refinery, the sub-tasks include chemical process design, piping design, and structural design. To reach these milestones, each sub-task involves the processing and communication of information between and among design team participants. These sub-tasks are sequentially interdependent [Thompson 67]—that is, the output of a given task is the input for a succeeding task. Thus, the sub-tasks can be represented in a precedence network.

Because our intention is to model organization structure rather than to automate design, we use an abstracted description of tasks. Each sub-task description includes the magnitude of the subtask, expressed in terms of the expected number of communications needed to complete the task; precedence constraints with related tasks; complexity (high, medium or low); variability (high, medium or low); percentage completed; and budgeted duration. In addition, we introduce the notion that both communication and information-processing for a given task will be most effectively performed if the information is represented in an appropriate natural idiom (e.g., text, schematics, 3-D Geometry) . For instance, dimensional coordination is best done with geometric rather than textual representations.

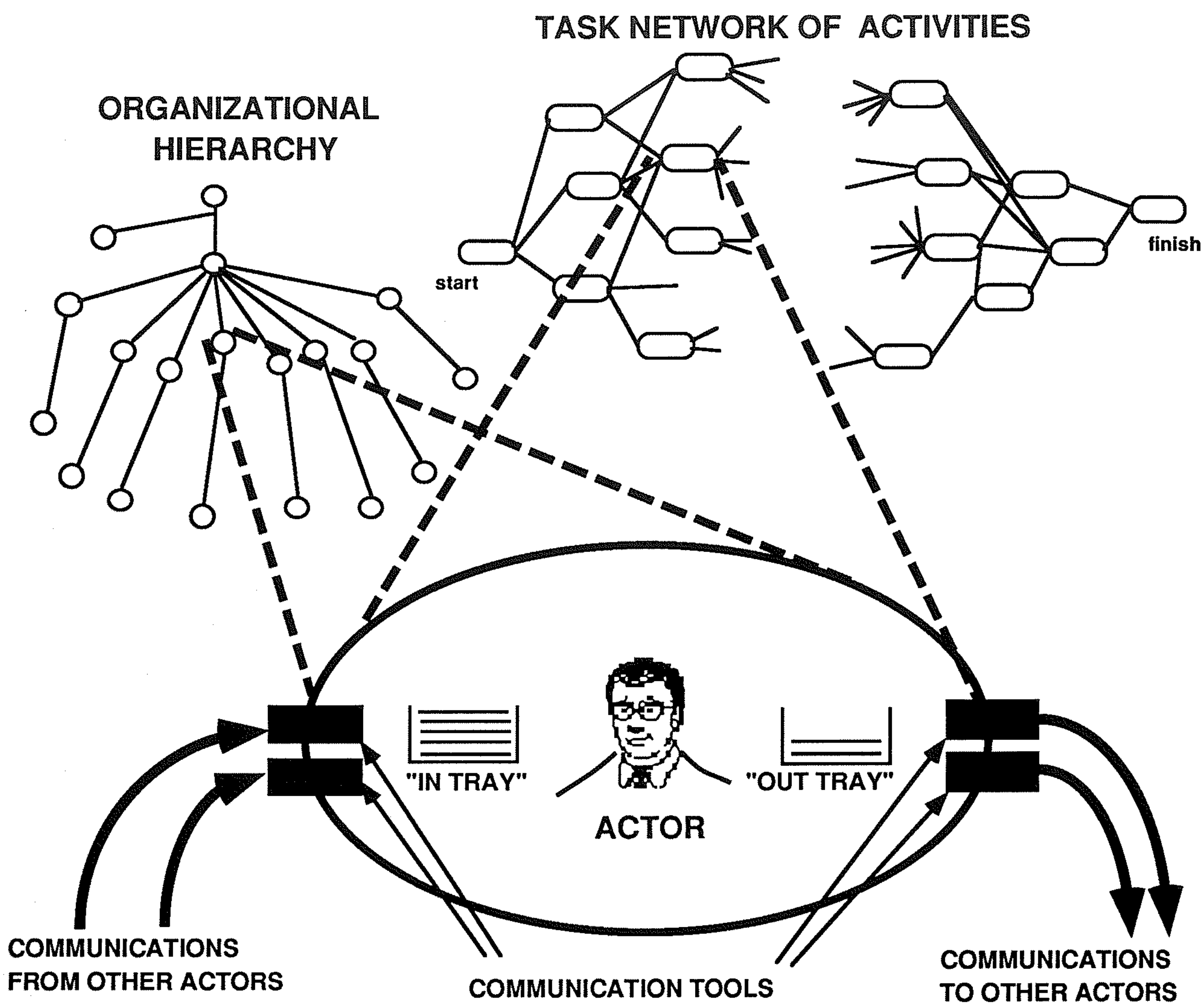

Figure 2. Overview of the VDT. VDT models the design task, actors, organization structure, and communication tools. The design task is broken down into a series of subtasks with precedence relationships and responsible actors. Actors are modeled as information processors with rules for attending to communications waiting for the actor's attention in an "in tray," and rules for deciding which communication tool to employ for sending communications to other actors via an "out tray." The organization structure is defined in terms of communication paths and the level of the hierarchy at which reviews and approvals can be made. Communication tools, such as meetings, telephones, voice mail, electronic mail, file sharing, etc., are modeled in terms of attributes such as synchronicity and bandwidth for communications involving different natural idioms (e.g., text, schematics, 3-D geometry). Subtasks are processed as chunks of information termed "communications" in a stochastic, discrete event simulation.

Communications

Tasks involve the processing and communication of information. We define a "communication" to be the elementary packet of information which is processed and communicated during the accomplishment of tasks. Each communication is associated with a series of discrete events in the VDT simulation. Individual communications have attributes including time stamp; author; recipient; distribution list; natural idiom (e.g., text, schematics, plans); variability of the associated task; action to be performed on the message; size; and priority.

Tasks are comprised of three basic types of communications: routine communications, exceptions, and noise. Each sub-task consists of a planned series of "routine communications," which carry the information required to perform pre-determined design, review, and approval sub-tasks. When failures occur, "exceptional communications" or "exceptions" [Galbraith 77] are generated by actors in the VDT. These exceptions direct remedial design, review, and approval activities. Of course, the more exceptions that occur, the longer the duration of the sub-task. Finally, the VDT recognizes that some communications received by individuals are irrelevant to accomplishing the task. Nevertheless, sorting through and discarding these communications, called "noise", consumes time of design-team participants; therefore, noise must be included in the model.

Not all communications are of equal importance for the completion of a given task. Each communication is assigned a priority (high, medium, or low) at the time of transmission; this influences how quickly the receiver will attend to it. Routine communications and exceptions for approval or coordination are assigned priorities at the time that they are received by an actor, based on the task descriptions or the nature of the exception. Remaining work to complete an interrupted task or exception is sent to the responsible actor with revised—in this case, increased—priority.

Actors

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

Actors perform the following functions:

1. *Select communications from an "in-tray".* Managers have limited time and attention to allocate to both routine activities and exceptions, and limited information with which to determine the importance of communications; i.e, managers are boundedly rational [Simon 76]. Managers in the VDT have an "in-tray"—a metaphorical, dynamic queue of communications through which any attempt to communicate with the manager must pass. Managers must decide which communications in the in-tray will be addressed immediately, which will be delayed, and which will be discarded. According to our limited field observations,

design managers appear to evidence a characteristic pattern in the way that they pay attention to waiting messages and the way they dispatch messages using particular media. For the selection of communications from an in-tray, the following initial values were used to model design managers' attention rules in VDT:

Basis for Choice	**Percentage of Time Used**
Priority alone	50%
Length of time in in-tray, weighted by priority	20%
"The next item noticed"—i.e., the item lying on top of the manager's desk (or on top of the manager's in-tray stack in the model)	20%
Random selection of items from the in-tray	10%

Table 1—Managers' attention rules for items in the "in-tray".
The VDT models each manager as stochastically attending to communications from the stack of communications in their "in-tray" at any given time, using the criteria shown in this table in descending order of likelihood. These numbers are derived from limited field observations of design managers and were used uniformly for all managers as a starting point for the initial validation of the model. They can, if desired, be customized to reflect the attention rules of a given manager more accurately (e.g., the first author generally reads all e-mail communications before attending to other communications).

2. *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 capabilities of an actor and the requirements of the task or exception.

3. *Send communications to an "out-tray" for distribution.* Actors (stochastically) select tools (described in the following section) to send communications to other actors. In the VDT, actors use the following criteria for choosing a tool:

    - *message priority*—synchronous tools like telephone are used for high priority communications;
    - *primary natural idiom in message*—different tools have higher or lower bandwidths for different natural idioms, e.g., facsimile is preferred to telephone for sketches of schematics, and CAD data file transmission is preferred to either for communication of geometry.
    - *proximity of sender to recipient*—if sender and recipient are in close physical proximity, face-to-face meetings are more likely to be used for communication.
    - *cost*—a high, medium or low cost is assigned to each tool; other things being equal, the least expensive tool is used.

If application of these criteria leads to a deadlock in choosing a tool, then one of the tools is selected stochastically, and the priority of the message affects the probability that a given tool will be selected to communicate it, as shown in Table 2.

Message Priority **Communication Tool to be Used**	***High***	***Medium***	***Low***
Meeting	35%	15%	10%
Phone	35%	30%	25%
Fax	10%	15%	10%
Mail	15%	35%	53%
E-Mail	3%	3%	2%
Video	2%	2%	0%
Totals:	**100%**	**100%**	**100%**

Table 2—Probabilities for stochastic selection of communication tools.
If criteria based on message priority, natural idiom in message, proximity of sender to receiver, and cost do not yield a clear choice of a communication tool, then the above probabilities are assigned based solely on message priority, and selection of a communication tool is performed stochastically via Monte Carlo simulation. These values are based on our limited field observations of design managers, and can easily be modified.

4. *Generate activities to coordinate with other actors*, based on the need for approval, coordination to obtain or share additional information, requirements for periodic or percentage-completion updates, and requirements for milestone review. Exceptions are generated when there is a mismatch between an actor's capability to process a particular communication and the communication's requirements.

Tools

Each communication is transmitted via a tool selected by an actor. There is a literature on individual and organizational choice of technology. In a recent review of this literature, Fulk and Boyd [Fulk 91] suggest that selection of communication tools in organizations is influenced both by media richness and by social preferences and norms in organizations. However, there is no theory that links task characteristics and managers' choice of technologies [Fulk 90]. Attempts to analyze these links have been hampered by a holistic or "object-centered" approach to technologies [Nass 90].

Therefore, rather than treat each communication tool as analytically indivisible, the VDT framework represents each tool in terms of values on a set of variables that are theorized to affect both the choice of tool and the results of that choice. The adoption and behavior of tools is then defined in terms of the relationships among the tool variables and the characteristics of the task, actors and organizational structure. In the present version of the VDT, tools are characterized by their: *synchronicity* (synchronous, partial, asynchronous); *cost* (low, medium, or high); *recordability* (whether or not a permanent record of the communication is available routinely); *proximity to user* (close or distant); *capacity* (volume of messages that can be transmitted concurrently); and *bandwidth* (low, medium or high) representing the capability of the tool for communicating information represented in each of the *natural idioms supported* (i.e., text, schematics, etc.).

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

Structure

Structure is defined via a set of attributes of and relationships among actors. There are three aspects of structure that can be included in the VDT model. *Hierarchy* is implemented via reporting relationships between actors. *Level of centralization* is defined by a set of coordination policies that assign decision-making authority to actors for reviews and approvals. A centralized structure is implemented by policies that require routine or exceptional approvals to be resolved at high levels of the hierarchy. Decentralized structures vest authority in lower-level managers to approve the outputs of design subtasks; thus, in decentralized organizations, fewer communications are sent to and processed by high-level managers. This reduces both the need for communication and the need for information processing. Finally, *informal structure* can be implemented via "social" relationships between actors. (Informal structure was not employed in the example application of the VDT described in this paper.)

Organization Theory and VDT

Organization theory provides a number of predictions concerning the effect of task, communications, actors, tools, and structure on organizational performance. The VDT is designed to implement these theories in a computational model. The model can be exercised both to test established theories of organizations and to suggest new theories.

Contingency theory of organizations posits that there is no one best way to organize. The optimum structure for an organization depends upon the values of variables describing its task and environment. Jay Galbraith's information processing theory of information flow and exception processing in organizations [Galbraith 77] derives from the contingency theory school. In the present research, the VDT is used to model and test predictions from Galbraith's model.

Galbraith theorized that the performance of an organization is affected by the structure and behavior of its information processing nodes and its communication channels. When all of the information required to complete a task is not available at the responsible node, an "exception" arises—i.e., the actor must communicate with a supervisor or peer to obtain the incremental information needed to complete the task. Hierarchical or legitimated lateral relationships define the formal channels that can be used to communicate these "exceptions." The organization begins to fail when either a channel (modeled as the aggregate capacity of all communication tools available across a given hierarchical or lateral relationship in VDT) becomes overloaded with exceptions to transmit, or when one or more nodes (modeled as individual or subteam "actors" in VDT) cannot process exceptions as rapidly as they arrive.

Galbraith makes a number of predictions about the effect of task, structure, and tools on the organization's demand and capacity for information processing. Most important for the present results is Galbraith's discussion of exceptions. When subteams' tasks are mutually interdependent, lower level managers may lack the global perspective to resolve exceptions that arise and formal authority for resolving exceptions may be retained at high levels of the hierarchy. When this occurs, high level managers will be called on repeatedly to resolve exceptions. A "centralized" organization structure in which the authority to resolve the most frequent types of exceptions is retained by senior managers can function for routine tasks with little mutual interdependence. However, if the subtasks to be performed by the organization are complex, unpredictable, and highly interdependent—as in engineering design activities—Galbraith's theory predicts that high-level nodes (senior managers) will become overloaded with "exceptions" to process, and the channels connecting them to middle and lower level managers will become gridlocked with communications.

Galbraith suggests that one set of solutions for managerial and channel overload includes decentralization of decision-making authority and the introduction of lateral communication. These structural changes should lead to a reduction of the number of exceptions to be processed by higher levels of the organization, which should result in decreased task duration.

A second set of solutions to reduce overload is the introduction of communication technologies that enhance channel capacity. If information flows more readily among organizational participants, actors will not have to wait as long for critical information.

Voice mail is modeled in VDT as an asynchronous communication tool—i.e., the intended receiver of the message does not have to be "idle" or available at the time the message enters the in tray to receive the communication. Voice mail also reduces social communications or "noise," so that the size of voice mail communications and the time taken to process them when the manager decides to attend to them, are both smaller. Moreover, voice mail messages may be sent out to many recipients in parallel. Thus, just as in real organizations, adding voice mail should increase channel capacities and thus reduce duration for either centralized or decentralized organizations.

In this paper we present an experiment to model the impact of decentralizing authority for approvals and of adding voice mail as a communication tool available to actors in a design team. Additional predictions that can be derived from Galbraith's model and tested by the VDT include:

- The greater the level of task complexity, the greater the number of exceptions.
- The greater the task interdependencies, the higher the level at which exceptions will be resolved.
- The greater the capacity of available tools, the lesser the likelihood of delays along critical paths.

The flexibility of the VDT also allows one to test a number of other researchers' theories derived from organizational research. Some examples are:

- The greater the fidelity of the output of a tool, the lesser the number of exceptions [Nass 90].
- The better the match between the natural idiom of the tools and the desired idiom of the actor, the greater the productivity.
- The more homogeneous a team's experience levels, the more efficient the performance of the team [Katz 78, 82], [Nass 92].

The VDT model permits a straightforward testing of these kinds of hypotheses, because the model explicitly represents and reasons about task complexity and interdependence, information processing nodes ("actors"), communications channels ("hierarchical relationships" together with "communication tools"), and predicts the rate at which exceptions ("communications") are transmitted and processed. This richness of representation in the model permits the verification and development of a wide variety of organizational theory.

Hardware and Software Implementation of VDT

The VDT is implemented as a symbolic model using object-oriented programming techniques. It has a set of objects with attributes and behaviors to define the design project and its subtasks, the actors who perform the information processing tasks that comprise design, and the communication tools available to each actor. Organizational structure emerges from the authority provided to each actor and the channels along which the actor can send and receive communications. The outputs of the model—subtask and project duration—are represented in terms of number of clock ticks (see Figure 1). The model is formal in that it includes the basic concepts of, and predicts behavior based on, a set of widely accepted theories. The model was implemented on a Sun Microsystems IPX Sparcstation using the *Knowledge Engineering Environment (KEE)*, and the *SimKit* discrete event simulation system, both from IntelliCorp.

The model entities all have stochastic behavior. The values of many actor and tool attributes can be one of a set of discrete alternatives or a number from a range. In a given run of the model, these values may be determined by rules (e.g., rules which relate actor attributes to the attributes of a communication), or they may be determined by Monte Carlo simulation, based on a probability distribution set by the user. The discrete attribute alternatives, numeric ranges and probability distributions used in this initial experiment were all derived from our limited initial field observations of actual engineering design teams.

When a high-level task is initiated in the simulation model, an initial message is sent from the design manager to the various project teams requesting information. Each team then receives an inquiry message, may generate further inquiries while processing this message, and eventually responds. When a task finally completes, the next task in the project can be initiated, either by the manager or by some other actor.

The model computes activity duration numerically in simulation clock units each of which corresponds to about 1 minute of an actor's time. Since each simulation run contains many stochastic "decisions," the durations generated by a set of runs carried out with the same task, actors, organization structure and communication tools will vary slightly around a mean value. As shown in the validation section below, we found that we could get very close to a converging mean value by averaging the values from three runs of the model for each set of values of the independent variables.

VDT records, and the investigator can inspect, the status of every object throughout the project. We have chosen to focus on one dependent output variable, the overall time for the Virtual Design Team to complete a project. Since many activities are performed concurrently, this overall duration corresponds to the length of the longest or "critical" path through the network of subtasks. The sum of the durations of all subtasks needed to complete the project is also available and can be used as a rough measure of the project's design cost (since the principal element of cost for a design project is the designers' labor).

Validation

In our validation experiment, we treated the VDT modeling parameters used to define the actor and task descriptions as constants. These are set by the user to model the subtasks comprising the specific task for the team (design of a petroleum refinery), and the attributes of the managers and subteams that will be employed to complete this task. The attributes defining organization structure (hierarchical relationships among actors and levels of authority for processing routine and exceptional communications), together with the communication tools available to actors, are treated as independent variables. These are set at different values to model, e.g., different levels of centralization; their impact on the duration of the individual subtasks and the overall project duration (the dependent variables) is then assessed.

As indicated above, VDT attributes have discrete qualitative values, such as (one-of "high", "medium", "low") or (one-or-more-of "text", "schematics", or "plans"), etc. 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. A principled but limited factorial analysis was used to validate the system's internal consistency: For our validation experiment, we selected two variables—level of centralization of decision making, and presence or absence of voice mail—predicted by Galbraith's theory to affect project duration.

To model different levels of centralization, we varied the level in the hierarchy at which design approvals were handled between *subteam managers* (decentralized) and the *design manager* (centralized). To give actors voice mail capabilities, we created a new tool with the attributes: *asynchronous, low cost, recordable, near, high capacity, high bandwidth for text and low bandwidths for schematics and geometry*. Values of all other variables in the model were held to an average value such as "medium". This form of sensitivity analysis is based on the method of [Box 78], and was also used by [Masuch 89]. Our validation experiment proceeded as follows:

1. Select two relevant variables to test. Set all other variables at average values.
2. Use Galbraith's theory to make a qualitative prediction—i.e., predict the direction of change in project duration from the baseline case— for the values of the two test attributes.
3. Conduct a set of three simulations of VDT for the base case and for each other combination of values for the two test variables.
4. Compare the simulated vs. theoretically predicted results using standard statistical measures of significance.

In our validation experiment, we modelled a relatively routine, 3-year, petrochemical design project. The total design and construction cost of the project is approximately $130 million. The design project has a budget duration of twenty months and, at its peak, involves approximately 120 managers, engineers, designers, and support staff located in two offices on opposite coasts, all from within the company. All actor and task descriptions were fixed and derived from this project. The pre-defined rules for attending to messages in the in-basket and choosing technologies were initially derived from a series of field interviews on the project and then compared to managerial behavior in another, $500M petrochemical design project. There was good consistency in managerial behavior across the two projects, so that we felt comfortable using the observed values as initial settings for these parameters [CohenG 92]. Clearly, this is one place where the model will need to be calibrated over time for this and other managerial domains.

The two independent variables in our experiment were the level of centralization (hierarchical relationships among actors and levels of authority for processing routine and exceptional communications) and the presence or absence of voice-mail. (Note that the project we simulated for this validation exercise was decentralized and had voice-mail available to its managers, so that the lower right hand cell in Figure 3 should be viewed as the base case.) By matching different levels of centralization with the possibility or impossibility of using voice-mail, we examined the impact of these two variables on the duration of individual sub-tasks and overall project duration, two critical measures of design team performance in the industry.

The results of the simulations that we ran are shown in Figure 3, below, together with the predictions from Galbraith's theory [Galbraith 77] about the impact of these variables on project duration.

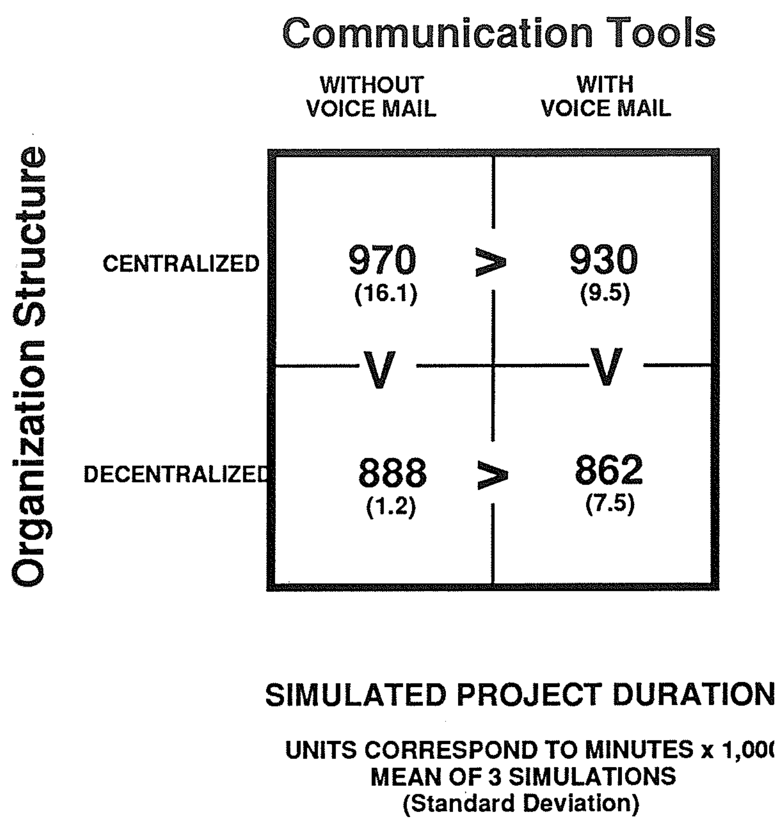

Figure 3. Validation of VDT vs. Theory for a Real Project Organization. VDT was used to model a 120-person design organization tasked to design a petroleum refinery. This model of a realistic design team and task was then used to simulate the effect of changing the organization structure, introducing voice mail, and both simultaneously. The lower right hand cell represents the base case for the organization modeled in this experiment. The ">" signs represent decreases in duration between cells (or increases in the "<" direction) predicted by Galbraith's information processing model of organizations [Galbraith 77]. As can be seen in this figure, the simulated results agree with the changes in duration predicted by Galbraith's theory for all four inter-cell comparisons.

As can be seen from Figure 3, the results are in clear agreement with Galbraith's model.

- A two-way analysis of variance indicates that, as predicted, centralized decision-making leads to longer task duration than does decentralized decision-making ($M = 950$ vs. $M = 875$; $F(8,1) = 164.11$; $p < .001$).
- Also as predicted, the presence of voice mail increases the speed of the project ($M = 862$ vs. $M = 888$; $F(8,1) = 32.06$; $p < .001$). The interaction was not significant ($F(8,1) = 1.44$; $p > .25$).

- For both centralized and decentralized organization structures, voice mail improves performance, as predicted ($t(4)=3.7$, $p < .01$, and $t(4) = 5.9$, $p < .01$, respectively).

Also of note is that, despite the number of elements of the model that are operationalized stochastically, the standard deviations in the four conditions are all extremely small (all less than two percent of the means), suggesting that the VDT model is very well- behaved.

Running time of the VDT Model

A typical case run has 24 activities, 17 actors, about one million simulation events, and takes about 90 minutes to run on a 64 MB Sun IPX workstation. We also conducted several runs with 90 activities; each of these runs required several hours to complete, but produced qualitatively identical results. The 90 activity project is approaching the practical limit of our current hardware and software environment, without optimizing the VDT system for processing speed. However, we believe that 90 activities is probably close to the optimum level of detail at which to model engineering design tasks, such as refinery design, for the purpose of analyzing their organization structures and information processing tools.

Related Work

Several investigators have worked in the general area of modeling organizational theory. [Malone 90] provides a comprehensive review of the use of information technology in organizations and its interaction with organizational structure. The review suggests a strong interaction between information technology, organization structure, and the performance of organizations.

The pioneering work of Masuch and LaPotin resulted in a symbolic, simulation model of the commitment, cognitive capacity and structure of actors performing simple tasks in a hypothetical organization [Masuch 89]. This work builds on Simon's bounded rationality theory but the authors do not emphasize information processing, attention rules or exceptions, as does VDT, nor do they report comparisons of the predictions of their model against real organizations. They contributed the limited blocking test design which we used.

Carley et al [Carley 90] discussed the use of an artificial intelligence-based model of a small organization in which intelligent agents communicate and cooperate to perform a distributed decision-making task. Their research, however, focuses on examining, at the micro-level, the three-way relationship between individuals' skills, job requirements, and coordination schemes, rather than predicting the impact of organizational structure and communication tools on the performance of an organization, as we do. Moreover, the limitations of their description of both tasks and agents prevents their framework from modeling the behavior of full scale organizations.

Discussion

The VDT simulation model explicitly allows an investigator to explore fundamental questions of engineering practice that have previously defied systematic analysis. No techniques or even guidelines currently exist to analyze the impact on team performance of a proposed organization structure and set of communication tools for performing a given design task. It is necessary to implement the organization and the technology in one-time, costly natural experiments to test whether they achieve the desired objective. With the VDT simulation model, we have taken a small step toward using computer-based simulation tools to begin predicting, qualitatively, the effect on project duration of proposed changes in organization structure and information technology.

The object-oriented VDT model represents, and reasons in some 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 VDT is based explicitly on the information processing theories of Galbraith, Simon and March and incorporates data from our own limited observations of attention rules used by managers and factors affecting their choice of tools for communication. Based on the limited validation carried out to date, we believe that VDT models the information processing patterns of multidisciplinary design teams performing routine design tasks relatively well at this time. We will continue to refine and extend its architecture and knowledge base.

Our initial objective was to demonstrate that AI symbolic models can be used to analyze and predict some important aspects of the behavior of real organizations. We were confident from the beginning that we could model tasks, actors, organization structures and communications tools of the projects. An issue was comparability of results: How could we assess the theoretical or practical validity of model results? Because of the routine nature of the project we modeled and observed, we assumed that we could compare the information processing patterns of the project, predictions of classic theory, and the results of the simulation model. Our initial results demonstrate that the effects of change in structure and communication tools on organizational output are qualitatively consistent between practice, theory and the VDT simulation model.

We have chosen not to interpret the mean project duration from a set of simulation runs as an absolute, quantitative prediction of the duration for the design task to be executed by the real team under the assumptions used in the model runs. Rather, since the theory we have used makes only qualitative predictions about project duration, we have chosen to make only qualitative comparisons between the mean values from sets of simulations, each designed to model different assumptions about organization structure and information processing tools. We interpret the direction of the difference in mean project durations ("shorter" or "longer") as a qualitative prediction of the impact that a change, or set of changes, in the independent variables will produce in the duration of the design project. With additional validation and refinement, it may be possible to calibrate the key elements of the model well enough to begin generating durations that can be viewed as absolute, quantitative predictions of project duration, especially for routine design tasks.

In practice, decentralization of decision making may result in lower quality decisions because middle managers may lack the global perspective available at higher levels to resolve exceptions that arise. Galbraith's theory, and the current VDT model, are silent on the issue of decision making quality, so that they cannot model the trade-off between speed of information processing and quality of the team's output. The next version of the VDT that we plan to develop [Christiansen 92] will address this issue explicitly by representing and reasoning about the functional requirements of each subtask. This will produce predictions about the quality of verification and coordination in the design process—i.e., the extent to which interdependent subtask requirements have been adequately verified and coordinated by the Virtual Design Team.

We conclude that VDT can be used to model qualitatively the information processing patterns of engineering organizations performing routine design tasks. Obviously, this initial demonstration is limited in the organizations, tools and projects it has considered, and further work is needed to find its limits in these regards. Besides calibration and refinement of the existing VDT model, our future research objectives (in increasing order of difficulty) include the following:

- A number of organizations in other service industries, and in some representative continuous and discrete manufacturing industry sectors, have volunteered to collaborate with us to test the generality of the ideas in the current VDT. We will attempt to carry out such tests, adapting VDT as needed to model decision making in these other industry sectors. This should yield insights about the extensibility and generality of the VDT framework.
- We plan to validate the model's representational power and reasoning performance with more dramatically different communication tools, such as shared use of 3-D CAD product models, or the use of "groupware" tools that support both information processing and communication among specialist subteams engaged in computer-supported cooperative work (CSCW). VDT currently has many of the constructs needed to model the *communication* functionality of groupware tools but will need extensions to model the ways in which groupware tools—and conventional computer decision support tools—effect the speed and quality of *information processing* by their users.
- We will extend the model's representation of task and subtask requirements, and its reasoning about them, to generate a set of output measures related to the quality (as well as the speed) of organizational performance. We are now developing a generic project model in which we can represent not only the tasks and their elaborations at different level of detail but also the perspectives on the project held by different agents. We believe that an appropriate level of detail of task description is important for us to examine the behavior of organizations. The generic project model will allow us to represent tasks in a flexible way.
- Over the next five years, we intend to model a broader range of actor attributes, such as commitments, beliefs, goals, and degree of motivation, so that the model can capture the impact of organizational reward systems, and the kinds of culture or value systems that emerge through company and project turnover rates, time spent in different levels of the organization, educational backgrounds of actors, etc., on task performance. Agent-oriented programming, as used by [Carley 90] is

one possible way to do this. We are exploring the potential to use the *iAgents* framework [Jin 92], an extension of the Agent0 architecture developed by [Shoham 90], for this purpose.

By expanding the theory base of VDT and testing it in other industries, we will attempt to generalize VDT as an analysis tool that can eventually model and validate a wide range of organizational theory. We anticipate that VDT will become a robust vehicle for testing extant theories and generating new theories that can be applied to predicting the performance of organizations carrying out information processing tasks. Over time, we hope that VDT will evolve into a useful tool for practitioners to use in analyzing the effect on their team's performance of alternative organization structures and communication tools.

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References

[Box 78] Box, G., Hunter, W., Hunter, J., *Statistics for Experimenters,* Wiley, New York, 1978.

[Bushnell 88] Bushnell, L.G., Serfarty, D., & Kleinman, D.L. "Team Information Processing: A Normative-descriptive Approach," In S.E. Johnson & A.H. Lewis (Eds.): *Science of Command and Control: Coping with Uncertainty,* AFCEA International Press, London, 1988.

[Carley 90] Carley, K., Kjaer-Hansen, J., Prietula, M., Newell, A., "Plural-Soar: A Prolegomenon to Artificial Agents and Organizational Behavior", *GSIA Working Paper,* Center for the Management of Technology, Carnegie Mellon University, December, 1990.

[Christiansen 92] Christiansen, T., "The Virtual Design Team: Using simulation of information processing to predict the performance of project teams," *CIFE Working Paper # 15,* Center for Integrated Facility Engineering, Stanford University, June, 1992.

[Clancey 89] Clancey, W.J., "Viewing Knowledge Bases as Qualitative Models," *IEEE EXPERT*, Summer, 1989, pp. 9-23.

[CohenG 91] Cohen, G.P., and Levitt, R.E. "The Virtual Design Team," Proceedings of the ASCE Construction Congress 91, American Society of Civil Engineers, Cambridge, MA, 1991.

[CohenG 92] Cohen, G.P., "The Virtual Design Team: An information processing model of coordination in project design teams," PhD dissertation, Stanford University Department of Civil Engineering , 1992.

[CohenM 86] Cohen, M. D., Artificial Intelligence and the Dynamic Performance of Organizational Designs, " in *Ambiguity and Command: Organizational Perspectives on Military Decision Making,* March, J.G., and Weissinger-Baylon, eds., Pittman, Boston, MA, 1986, pp. 53–71.

[Coyne 90] Coyne, R.D., Rosenman, M.A., Radford, A.D., Balachandran, M., & Gero, J.S., *Knowledge-based Design Systems,* Addison-Wesley, Reading, Mass., 1990.

[Crowston 90] Crowston, K., "Modeling Coordination in Organizations," *MIT Sloan School of Management Working Paper No. 3228,* 1990.

[Fulk 90] Fulk, J. & Steinfeld, C. (Eds.), *Organizations and communication technology.*, Newbury Park: Sage, 1990.

[Fulk 91] Fulk, J. & Boyd, B., "Emerging Theories of Communication in Organizations," *Journal of Management, (17) 2,* 1991, pp. 407-446.

[Galbraith 77] Galbraith, Jay., *Organization Design,* Addison-Wesley, Reading, MA, 1977.

[Jin 92] Jin, Y., "i-AGENTS: Modeling Concurrent Decision-Making in Multiagent Teams", *CIFE Working Paper #16,* Center for Integrated Facility Engineering, Stanford University, 1992.

[Katz 78] Katz, R., "Job longevity as a situational factor in job satisfaction," *Administrative Science Quarterly, 23,* 1978, pp 204-223.

[Katz 82] Katz, R., "The effects of group longevity on project communication and performance," *Administrative Science Quarterly, 27,* 1982, pp81-104.

[Kunz 89] 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.

[Levitt 90] Levitt, R.E., "Model Based Planning: An Engineering Perspective," Proceedings of IEE Conference on Knowledge-Based Planning, Brighton, UK, 1990.

[Levitt 91] Levitt, Raymond E., Yan Jin and Clive L. Dym, "Knowledge-Based Support for Management of Concurrent, Multidisciplinary Design," *Journal of Artificial Intelligence in Engineerng Design, Analysis and Manufacturing, (5) 2,* 1991, pp. 77-95.

[Malone 90] Malone, T. W., and Crowston, K., "What is Coordination Theory and How Can It Help Design Cooperative Work Systems," *Proceedings of the Conference on Computer Supported Cooperative Work*, Los Angeles, California, October, 1990.

[March 58] March, J.G., and Simon, H.A., *Organizations.* New York: Wiley, 1958.

[March 88] March, J.G., "Decisions and Organizations," Oxford, Basil Blackwell, 1988.

[Masuch 89] Masuch, M., LaPotin, P., "Beyond Garbage Cans: An AI Model of Organizational Choice," *Administrative Science Quarterly,* 34, pp. 38-67, 1989.

[Mintzberg 73] Mintzberg, H. *The Nature of Managerial Work,* Harper and Row, New York, 1973.

[Mintzberg 79] Mintzberg, H., *The Structuring of Organizations,* Prentice Hall, New Jersey, 1979.

[Nass 90] Nass, C. I. , & Mason, L., "On the study of technology and task: A variable-based approach," in J. Fulk & C. Steinfeld (Eds.), *Organizations and communication technology* , Newbury Park: Sage, 1990, pp. 46-67.

[O'Reilly 87] O'Reilly, C.A., and Chatman, J.A., "Message Flow and Decision Making," in *Handbook of Organizational Communication,: An Interdisciplinary Perspective,* Jablin et alia, editors, Sage Publications, Beverly Hills, CA, 1987, pp. 600-623.

[Shoham 90] Shoham, Y., "Agent-Oriented Programing," *Technical Report STAN-CS-1335-90,* Department of Computer Science, Stanford University, 1990.

[Simon 73] Simon, H.A., "Applying information technology to organization design," *Public Administration Review, 33,* 1973, pp. 268-278.

[Simon 76] Simon, H.A., Administrative behavior: a study of decision-making processes in administrative organization, New York: Free Press, 1976.

[Sproull 91] Sproull, L., and S. Kiestler, *Connections: New Ways of Working in the Networked Organization,* MIT Press, Cambridge, MA, 1991.

[Thompson 67] Thompson, J.D., *Organizations in Action,* McGraw-Hill, New York, 1967.