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Competence Models and Self-Organizing Systems: Towards Intelligent, Evolvable, Collaborative Support

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ABSTRACT **A number of modeling perspectives are relevant to the design of intelligent, adaptive, and collaborative support for humans who work in complex sociotechnical, systems. We first describe the separate strands of normative models of activity and communication and self-organizing models of organizational adaptation to technology, and then braid them together to arrive at a coherent framework for the analysis and modeling of collaborative work in complex systems. From this integrated framework, we propose requirements for the design of collaborative support and develop these ideas in the context of the System Workbench for Integrating and Facilitating Teams (SWIFT) architecture.**

I. INTRODUCTION

The Team Engineering Analysis and Design (TEAM) project is a collaboration between engineers and social scientists that seeks a principled, model-driven approach to the analysis of work groups in complex problem solving situations and the design of computer support systems for such groups. To design appropriate support systems, a fundamental understanding of activities and associated media and tools is required. TEAM proposes a *competence-centered* approach to modeling interaction that incorporates both analysis of current practices (a user-centered perspective that is situated and empirical) and a specification of normative models of activity and communication (a normative task-centered perspective).

In this paper we discuss three separate strands of work that reflect three interrelated perspectives on analysis and modeling of activity: Activity requirements (a normative model of activity and associated system, information, and artifacts), activity production (in terms of attention, inference, and performance), and activity evolution (in terms of activity, norms, affordances, and networks). These interrelated perspectives are then braided together to account for team performance in a particular context.

The rest of this paper is organized as follows. Section II describes the process of engineering design review (Case et al., 1992) that will be used as a specific context for analysis. Section III describes the three different perspectives on activity modeling and their integration. Section IV proposes a methodology for data collection, analysis, and modeling, and Section V speculates on how such an approach can inform the design of the System Workbench for Integrating and Facilitating Teams (SWIFT), an architecture for the construction and deployment of collaborative support systems (Lu et al., 1993).

II. ENGINEERING DESIGN REVIEW AND ARMS [1]

The specific engineering design context for this research is the design and construction of a facility requested by the Air Force and carried out by the Army Corps of Engineers. The following sections elaborate on the participants, the design process, and the electronic review management system that mediated interactions between designers, quality assurance teams, and the Air Force "customer."

A. Participants in the Design Process

An Air Force base (the end-user AFB) initiates a design project by making a request to the Air Force Strategic Air Command (SAC). As is the case for many construction projects, SAC contacts an Army Corps of Engineers design project manager. This project manager is responsible for the design phase of a project and oversees a number of groups, including engineering design, cost estimation, and design quality assurance. And as is often the case, the actual design is done by an outside contracting firm referred to as the Architect/Engineer (A/E). Participants involved in the design process are from SAC itself, from the Air Force Base (AFB) "end-user" community, from Corps geotechnical, landscaping, cost estimating, design quality assurance, and construction quality assurance groups, and from the A/E firm. The construction project manager assumes responsibility in the subsequent construction phase.

B. Design Process

The design process itself, which is carried out by the A/E and monitored by the design project manager, SAC, and the end user, is structured as a series of sequential phases that are not necessarily contiguous.

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[1] This section adapted from Case et al., 1992

For this construction project, the following phases occurred: project book (2 weeks), project definition (3 weeks), initial submittal review (2 weeks), 60% onboard review (2 weeks), final design (3 weeks), final design late (3 1/2 weeks), first backcheck (1 1/2 weeks), and second backcheck (1 week).

C. The ARMS System

The Automated Review Management System (ARMS) is a software package that manages design review comments and responses for the Army Corps of Engineers. Reviewers, from the Corps, SAC, or the end-user facility, make comments on aspects of the A/E's design. Typically, someone from one of the design project manager's groups will originate such a comment, and SAC and the end-user Air Force Base facility will state their opinions of the remark using a standard response protocol. The comments are forwarded to the A/E via the design project manager. Also through ARMS, the A/E responds to each comment, also with a standard response protocol.

Although the use of ARMS is a required part of design in many Corps of Engineers projects, it is important to realize that its use reflects only portions of the design process. ARMS focuses on "macro" consensus management issues between fairly large "sender units" such as SAC and Design Quality Assurance; the "micro" negotiations within a sender unit are unknown. No data are available on face-to-face meetings or review conferences. Nevertheless, ARMS provides a complete picture of the interactions that it does support, and is thus quite useful as a starting point for analysis. Table 1 shows a sample sequence from ARMS (see Case et al., 1992 for further details and analysis).

Table 1. Sample sequence from ARMS.

Sequence	Component Segment
Desk chairs need to be dual purpose for both leisure and desk seating.	Comment
>SAC: CONCUR	SAC response
>CORPS: CONCUR	Corps response
>A/E Response: DONE	A/E response
SEE LOCATION CODE C8XD UPHOLSTERED DESK ARMCHAIR	A/E elaboration
>BACKCHECKED for 1st Backcheck (approved) by XXX on Wed Mar 4 19xx	First backcheck

III. Perspectives on Activity Modeling

Three different perspectives on activity provide insight into cooperative work processes. One perspective focuses on activity requirements: Normative models of activity rooted in the human-machine systems engineering literature. The second perspective provides further insight into activity production. The third perspective includes an analysis of the shaping of activity over time in the context of technological affordances and group norms (i.e., activity evolution).

A. Activity Requiremenrs

A variety of human-machine systems engineering models seek to account for human activities in the supervisory control of complex dynamic systems (Jones, Patterson, and Goyle, 1993). One model is the operator function model (Mitchell, 1987), a heterarchic-hierarchic network of nodes (activities) connected by arcs (system triggering events). The elements of this model have been elaborated further into a knowledge-based architecture for cooperative support called ISAM (Jones, 1994; Jasek and Jones, 1994). The major elements of ISAM are Activity Objects, System Objects. Information Objects, and Artifact Objects.

Activity Objects represent "generic" features of activity such as name, purpose, hierarchical relations to other activities ("parents" and "children"), priority, temporal information, and preconditions and postconditions. Such conditions may include references to other activities or other types of objects as described next.

System Objects represent components of the system being controlled that are acted upon by human operators. Information Objects represent dynamic and temporary sources of information such as telephone calls and display pages. Artifact Object represent the procedures and forms that act as inputs, guides, and outputs of activity.

The ISAM architecture provides a framework within which the semantics of a particular domain can be instantiated. Thus, analysis focuses on (1) the activities that competent practitioners should engage in given various system events, (2) the hierarchical decomposition of major activities into sub-activities and eventually to the level of the actual actions ("syntax") performed in the domain, and (3) the system components, information, and artifacts that may trigger, guide, be referred to, or are outputs of these activities. A specific example of ISAM applied to satellite ground control is described in Jasek and Jones (1994).

B. Activity Production

Our analysis is also based on a view of activity as locally produced and managed. A local management view of activity contrasts with more standard problem-solving or planning approaches in which (a) actions are seen as planned prior to enactment rather than in the process of enactment; and (b) problems are solved within stable, context- independent representations rather than locally constructed, evolving representations (see Agre & Chapman, 1987, 1990; Greeno, 1993; Lave, 1988; O'Keefe & Lambert, in press; Suchman, 1987). Within a local management view, participants are seen as constantly engaged in a process of reinterpreting the activity and coordinating their interpretations of the current situation with those of other participants.

Consistent with this perspective, action is seen as guided by processes of attention and inference. As Mead (1934) suggested, the coordination of social action is grounded in a reciprocal process of making indications to others, indications which guide attention and therefore inference. In a contemporary reformulation of this approach, Sperber and Wilson (1986) have argued that such a process of making indications is the basis for communication: communicators' inferences about the goals and plans of their partners are guided by such ostensive indications (for a more complete exposition of this view, see Jacobs, 1985).

Coordinated action, then, is made possible through the reciprocal organization of such indications. The relationship between representations of a situation, including representation of the other interactants and their goals, and performance is mediated by a logic of message design which articulates the relationship between ends and means and guides the adaptation of action to local exigencies (O'Keefe & Lambert, in press).

This view of activity and its organization was applied by Burke (1986) in her study of the effects of alternative technologies on communication between experts and novices. Burke's results provided a detailed example of the ways in which attention and inference guide performance and the coordination of behavior in activity.

C. Activity Evolution

The local production and management of activities, discussed above, implies that the effects of collaborative support technologies are not necessarily consistent across groups and over time. Hence in contrast to traditional research that is based on a premise of technological determinism, we propose that the uses and effects of communication technologies are better studied from an "emergent perspective" (Contractor & Eisenberg, 1990; Contractor & Seibold, 1993; Contractor, 1994). The emergent perspective is based on the assumption that the uses and effects of communication technology emerge on the basis of complex social interactions among users. Moving toward an emergent perspective -- and away from the univalent effects hypothesis associated with the technological imperative -- entails at least three requirements. First, it requires precise longitudinal examination of the group's norms surrounding the social practices of activity and coordination. For instance, groups using ARMS may evolve unique norms about the need for providing elaboration or backing to accompany problem specifications. Second, it requires a systematic identification of the affordances (or structural features) made possible by the introduction of collaborative technologies in work groups. For instance, collaborative technologies offer members the heretofore unavailable affordance of synchronously annotating the same design document. Third, it requires specification of the evolution of roles by actors in the work group. For instance, in the ARMS data discussed earlier, the Air Force Strategic Command may emerge as a liaison serving to broker disagreements between the A/E and the "end-user" Air Force Base. Taken together, these three requirements suggest that the modeling of activity evolution represents the articulation of reciprocal and dynamic relationships among social norms, affordances provided by collaborative technologies, and actors' roles (Contractor & Eisenberg, 1990). Consistent with our emphasis on an emergent perspective, the recursive interplay among social norms, affordances provided by collaborative technologies, and actors' roles, must account for how specific work groups assimilate technologies within their own streams of work activity. That is, an emergent perspective must be capable of explaining how groups with similar composition, working on similar tasks, perceive and use the same collaborative technologies differently (Barley, 1990; Lewis & Seibold, 1992).

Several theoretical perspectives have been spawned or appropriated by GDSS researchers: social presence (Short, Williams, & Christie, 1976), media richness (Daft & Lengel, 1986), social information processing (Fulk, Schmitz, & Steinfield, 1990), Adaptive Suucturation Theory (Poole & DeSanctis, 1990). Building on these perspectives, Contractor and Seibold (1993) offer Self-Organizing Systems Theory as an approach to model with precision the evolution of activity in work groups using collaborative technologies.

In general terms, Self-Organizing Systems Theory (SOST) seeks to explain the evolution of patterned activities in work groups that are initially in a state of disorganization. It offers a conceptual framework to explicitly articulate the underlying generative mechanisms and to systematically examine the processes by which these mechanisms generate, sustain and change existing activities or trigger new activities. The underlying generative mechanisms represent the mutually causal and often non-linear relationships between the work group's social norms, the affordances of the collaborative technologies, and the roles of group members.

While it is possible to verbally specify the generative mechanisms relating social norms, technological affordances, and members' roles, these descriptions in "everyday language . . . tend to have two related characteristics that limit their utility for unambiguous statements of theories: They are (1) richly evocative and (2) highly abbreviated" (Hanneman, 1988, p. 23). Hence any attempt at offering a more precise articulation of the generative mechanisms must necessarily look to mathematically specified equations to assess the long-term evolution of activities in work groups. Computer simulations provide invaluable assistance in predicting the evolution of activities because the generative mechanisms proposed by SOST, like most social science theories, result in non-linear equations. While human intellect is capable of articulating non-linear relationships, it is limited in its capacity to mentally construe the long-term appropriation patterns implied by these non-linear mechanisms (Hanneman, 1988).

D. Braiding the Strands

Competence encompasses the definition of activity requirements, production, and evolution. Activity requirements specify the nature of the activities that should be accomplished -- their interrelationships (e.g., hierarchic, precedence) and their preconditions, referents, and postconditions in terms of system objects, information, and artifacts. Given this overall specification of competent performance, each activity can further be analyzed in terms of activity production: the ways that, in the local circumstances, processes of attention and inference guide performance to meet activity requirements. Finally, sustained competence is defined by self-organizing systems theory.

An analysis of activity requirements in the ARMS study would include an articulation of design activities that in this case follows the Army's standard procedure for design review (e.g., project book, project definition, initial submittal review, and so on). For each of these major design review phases, more detailed activities are defined that eventually culminate in specific actions that affect the design itself (i.e., change the state of some system object), communicate information (i.e., dynamic creation of information objects), and/or provide documentation (i.e., update one or more artifacts). The interrelationships among activities are also specified such as prerequisite constraints, temporal constraints, and hierarchical relationships. Features of activities such as priority and responsibility are also defined. For example, for each design review phase (function), different participants engage in various sub-activities (e.g., requesting information on a change, using ARMS to justify their design decisions, changing the kinds of material used in the facility being designed). ARMS is an example of an artifact that is utilized throughout the design process to coordinate changes and provide justification for the design.

Burke's (1986) investigation provided a model for our analysis of the ARMS sequences we analyzed. Each ARMS comment was classified in terms of what kind of indication was given to readers in three areas: (1) specification of problem; (2) specification of solution; and (3) specification of backing. We assumed that elaboration in any of these areas reflected an assessment by the communicator that there was a lack of consensus regarding that particular issue, and so for each of these issues we classified the message in terms of the degree of elaboration of that issue. For example, each comment was evaluated in terms of the degree to which it specified what was problematic about the project or plans; it received a score of 1 if it lacked a problem specification, a score of 2 if it contained a general reference to a problem, and a score of 3 if it provided' a specific and detailed characterization of the problem. The degree of specification of solutions was similarly evaluated. In addition, the specification of backing was evaluated: backing refers to the mention of specific reasoning or resources such as regulations or authority that provide a rationale for a design recommendation.

We examined both patterns in elaboration of comments and relationships between comment design and comment acceptance/rejection. In general, we found that comments tended to either indicate a problem or a solution rather than elaborating both equally. Comments that contained more detailed specification of problems were more likely to elaborate backing than those with less problem specification. Comments that elaborated problems were more likely to elicit concurrence from the client (SAC), denial from the Corps, and explanations from the architect/engineer in charge of the project (A/E). Comments that elaborated solutions were less likely to elicit concurrence from SAC; they elicited more references to resources and explanations and less agreement from the A/E. SAC was less likely to concur with comments that provided backing, and the A/E was also less likely to include references or indicate agreement with comments that elaborated backing.

These findings support a view of performance as grounded in processes of situated attention and inference. In general, comments were designed to indicate rather than specify problems and solutions; moreover, comments tended to make either a problem or its solution the focus for consensus management. The process of managing consensus was not a simple matter of eliciting agreement or disagreement; instead the stances taken in responses were a function of the distinctive roles played by participants in the process of design review. Finally, backing played an unexpected role in the process of design review: rather than serving to facilitate consensus, instead it appeared to indicate areas of disagreement. This is consistent with the view of Jacobs and Jackson (1989), that participants elaborate their reasoning only in the context of actual or anticipated disagreement from others.

The ARMS study is a pilot study which addressed some issues in the use of collaborative technology. A full-scale study of the practice of design and design review would encompass a variety of observation and modeling activities. Such a methodology is described in the next section.

IV. A Methodology for Competence Models

As discussed above, some theoretical and empirical research has attempted to model the three separate strands of work representing activity requirements, activity production, and activity evolution. In the previous section, we have proposed that the integration of these three strands of work offers a more comprehensive specification of competent performance in work groups. The theoretical integration proposed above requires an elaborate methodology for empirical research and development. The process begins with an assessment of current activity requirements through the systematic observation of user communities. This includes the use of semi-structured interviews with users and tracking workflow to describe, analyze, and evaluate current user practices. This phase will result in the specification of a model for activity requirements, including the four elements of activity objects, system objects, information objects and artifact objects (discussed in Section IIIA). Next, the model for activity requirements observed among users will be critically evaluated from a competence theory perspective. In this stage, the observed activity requirements will be used to guide the specification of a normative model of activity production. The normative model is based on the premise that there are systematic local strategies for the competent accomplishment of certain functional requirements (discussed in Section IIIB). The activity evolution implied by the normative model of activity production can be modeled as a self-organizing system (discussed in Section IIIC). Simulations of this model will provide hypotheses about work group activity. These hypotheses should next be empirically tested in experimental user studies. The results of the computer simulations and the laboratory studies may lead to modifications in the proposed normative models for activity production. After this iterative process of theory development and empirical validation has been accomplished, the normative model of activity production is used to make specific recommendations for resources and user interface design. The development and deployment of these tools by users creates an opportunity for a new round of observation of user communities.

As we use this method to systematically study and adapt applications for different user groups, we will accumulate a set of instances that can form the basis for comparative studies and generalization across user groups. This integrated, general model can in turn function as a competence model for the design of general tools such as the SWIFT workbench (discussed below).

One final point to be emphasized about this methodology is that by envisioning the process of designing applications as a dialogue between the target user community and the application developer, it virtually guarantees the relevance and usability of the application. By according user studies a greater and more systematic role in the development process, we expect to achieve substantial gains in the ultimate acceptance of the application.

V. Implications for Design

The Systems Workbench for Integrating and Facilitating Teams (SWIFT) (Lu et al., 1993) provides a workbench for developers to define collaborative support systems and facilities for creating the end-user applications. It is a layered architecture that builds upon previous knowledge processing technology (Herman, 1989). In this section we propose some ideas on how the competent, self-organizing systems approach outlined in this paper can inform the design of the collaboration layer of SWIFT.

SWIFT focuses on synchronous, tightly coupled team decision making. The users of SWIFT include developers and end users; developers use the workbench to create applications for end users. The methodology discussed above focuses on the study of end user practices. Thus, this methodology is part of the process that SWIFT developers should perform in order to build applications.

Implications of activity requirements analysis include a developer's graphical interface to specifying activities and their attributes and relationships (visual programming of the model) including specification of user actions that can be tracked computationally. In "end user application mode", the team can view current activity requirements, navigate through the web of activities, artifacts, and so on, and perform substantive work in this environment including communication and delegation of tasks. Activity tracking provides a resource for intelligent support (e.g.. context-sensitive reminders).

Implications of activity production include for the developer's workbench, the specification of cues and information attended to as part of activity, and for the end user application, shared visualization of who is attending to what (which serves as a resource for efficient coordination of activity). This approach is in contrast to the Winograd and Flores (1988) approach of making intentions explicit.

Finally, an implication of activity evolution is that developers should be able to do predictive simulation modeling of the mutual influences of technological affordances and group norms. Thus, such dynamic simulation models can serve as analytical tools that are integrated into the design process.

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