



CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

**Transactive Memory
and Exception Handling
in High-Performance Project Teams**

By

Monique H. Lambert, Ben Shaw

**CIFE Technical Report #137
July 2002**

STANFORD UNIVERSITY

**Copyright © 2002 by
Center for Integrated Facility Engineering**

If you would like to contact the authors, please write to:

*c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020*

Transactive Memory and Exception Handling in High-Performance Project Teams

Monique H. Lambert, Ben Shaw

Abstract—This paper describes recent empirical research in which we examined the operation of transactive memory in a project team at the Jet Propulsion Lab that used real-time concurrent design processes to develop conceptual hardware designs for future Mars missions. Our preliminary findings suggest that in cases where information encountered by a team is clearly partitioned into distinct functional domains, a team with a highly differentiated transactive memory structure might constitute a good fit. However, in task situations where teams encounter new information that isn't easily partitioned and allocated into well-defined functional domains, a team with a less differentiated transactive memory structure might be needed for greater information "uptake." This empirical research constitutes input for further work aimed at combining formal models of exception handling and transactive memory into an integrated framework that can be used to represent and model the operation of distributed information and expertise in project exception handling.

I. INTRODUCTION

All complex engineering projects have certain schedule and performance goals. In spite of management's best planning efforts, however, exceptions or unexpected events often emerge during a project, which can introduce certain unanticipated risks to planned project and product goals.

Exceptions differ in type and affect project teams and project stakeholders in different ways. For an individual team member, an exception might be a lack of local information or expertise to complete an assigned task. For a firm, an exception might be the emergence of a disruptive technology in the market, which threatens to undercut market demand for a new product in the firm's development pipeline [1], [2].

Exceptions can stem from internal factors such as low team experience, poor coordination or overload. Alternatively, exceptions can stem from external factors such as sudden changes in customer requirements, a new competitor emerging

in the marketplace, or unanticipated changes in certain regulatory policies that impose new constraints on certain product technologies and/or manufacturing processes.

Exceptions can occur during different phases of the project life cycle, and can affect project activities and outcomes in various ways. For example, in the detailed design phase, a design team might discover conflicts between certain technical constraints, which can lead to costly re-design or re-scope of product features.

Regardless of the particular attributes of a given exception (i.e., type, cause and/or timing), unless decisions are made to ignore certain exceptions, each exception triggers a new problem-solving task, which typically requires the coordination of distributed information and expertise. Information needed to resolve exceptions might reside in the minds of other people, in documents, or in electronic sources. Alternatively, information necessary to resolve exceptions might need to be created, which might involve integrating information from different sources or running certain analyses. In some cases, new information can reveal that prior decisions or tasks need to be reworked, which creates emergent coordination and work. The net effect is that each exception—if attended to—takes attention and time to resolve. Thus, each exception holds a certain potential for generating emergent coordination and/or rework for managers and members of a project team.

Certainly, all project teams have some built-in capacity for handling a certain number of exceptions. However, prior empirical research indicates that when the exception-handling load on a project team exceeds the team's information processing capacity, project delays, quality problems and/or cost overruns can result [3]. The question that remains is, how should managers design and support project teams that are not only effective at handling the direct work requirements of a project, but are also effective at handling exceptions that inevitably emerge during a project?

In order for managers to be able to design and support project teams for effective exception handling, managers need insight into key properties and processes that affect a team's ability to efficiently coordinate information and expertise from a distributed set of sources.

In this paper we describe early findings from empirical research in which we examined how members of a multi-disciplinary project team at the Jet Propulsion Lab (JPL) coordinated certain technical information and expertise while developing hardware design concepts for future Mars science missions. To focus my observations of the team's information handling processes, I

M. H. Lambert is a Researcher in Manufacturing and Strategic Support (MSS) at Intel Corporation, and a Ph.D. Candidate in Engineering Management at Stanford University, Terman Engineering Center, M/C 4020, Stanford, CA 94305-4020 (e-mail: mhlamber@stanford.edu).

B. Shaw is a Ph.D. Candidate in Industrial Design at the Royal College of Arts in London, England, and a Visiting Scholar at the Institute for International Studies at Stanford University, IIS, M/C 6055, Stanford, CA 94305-6055 (e-mail: bgshaw@stanford.edu).

This material is based on work supported by the National Science Foundation under KDI Grant No. IIS-9980109, and by Intel Corporation. Any opinions, findings and conclusions or recommendations expressed in this materials are those of the authors and do not necessarily reflect those of the National Science Foundation or Intel Corporation.

drew upon transactive memory theory [4], [5] as a lens for examining: (1) how the team collectively structured and processed information during actual design work, and (2) how the distribution of information and expertise amongst team members facilitated or impeded team performance.

This research seeks to build upon current models of exception handling, which represent and model the impact of hierarchical exception handling mechanisms and centralized exception handling expertise on team and project performance [3], [6]. The goal is to apply the data obtained in the current empirical study as the basis for defining a precise set of team properties and behavioral mechanisms that reflect the operation and impact of exception handling mechanisms involving non-hierarchical, distributed information and expertise.

In the following sections, I briefly describe a formal model of exception handling and transactive memory theory. I continue with a description of the case study, and end by discussing some of the preliminary findings and implications of the study.

II. FORMAL EXCEPTION HANDLING MODELS

Formal models, such as the Virtual Design Team (VDT) agent-based computational model, explicitly represent the impact of exceptions and project team exception handling processes on project schedule, quality and cost [3], [6]. VDT models exception handling as an upward flow of exceptions and downward flow of decisions along a fixed exception handling hierarchy. Underlying this particular representational framework is the implicit assumption that the paths members use to retrieve exception handling information and expertise are relatively fixed, and that all relevant exception handling expertise is centralized in a relatively small set of members comprising the reporting hierarchy.

Although the VDT model contains a reasonable representation for exceptions that require managerial decision-making, the current exception-handling framework does not adequately represent exceptions that are handled *outside* of formal reporting relationships. Thus, the current VDT model has limited capabilities for representing and estimating the performance impact of more dynamic exception-handling processes that rely more heavily on the use of distributed (i.e., non-hierarchical) sources of information and expertise.

III. TRANSACTIVE MEMORY IN PROJECT TEAMS

My informal observations of project teams in the computer industry suggest that project teams vary in their “capacity” to handle different exceptions that arise during a project. My observations further suggest that differences in exception handling capacity are related to differences in properties of a team’s “transactive memory system.”

Transactive memory describes a specialized division of cognitive labor in which groups develop certain “patterns” for structuring and processing information within a group [4], [5], [7], [8]. These patterns, which represent how information is

allocated, stored and retrieved within a group, are based on members’ perceptions about how information and expertise is distributed (or stored) amongst members of the group [4], [7], [8].

The model of transactive memory suggests that groups encode, store and retrieve information in ways that resemble how individuals encode, store and retrieve information to and from individual memory. However, unlike individual memory processes, which are centralized and do not (typically) require verbal self-communication, group-level memory processes are distributed and facilitated by various communication interactions or transactions that occur between group members—hence the name *transactive memory*[9].

Prior empirical research on transactive memory provides evidence that groups that have more accurate perceptions about how expertise is distributed amongst members of the group perform better on collaborative tasks than groups that have less accurate perceptions about who knows what [7], [8], [10].

To date, much of the empirical work on transactive memory has been conducted using controlled, experimental studies of small groups comprised of two- to three-person teams working on relatively simple collaborative tasks. These experimental studies have emphasized specific elements of transactive memory, such as factors that contribute to the development of transactive memory [7], [8], and the effect of group training on transactive memory [10], [11]. Relatively little empirical research exists, which has examined the joint operation of transactive memory processes (i.e., encoding, storage, retrieval and integrative processes), and the relationship these processes have on the performance of industry workgroups in general, and engineering project teams in particular.

IV. MOTIVATION

In undertaking an empirical study of a project team’s transactive memory processes, my interest was in observing how certain information that the team encountered in its collaborative work eventually came to be distributed (i.e., encoded and stored) amongst various members of the team, or in other storage locations. I was also interested in observing what role team memory played in the team’s efforts to retrieve certain task-relevant information, which the team had previously encountered. Thus, my interest was in observing: (1) where new information was eventually stored within the team (if anywhere), (2) what mechanisms (if any) the team used to get it there, and (3) the extent to which team members “remembered” certain information items and/or remembered the location of certain information when attempting to retrieve the information at a later time.

My rationale for these particular observations was to establish some empirical basis for defining certain team properties and processes that affected the team’s “capacity” to encode, store and retrieve

information that was encountered by the team during collaborative work. Measures of the team's capacity to coordinate information and expertise in the context of collaborative, concurrent work would provide at least an initial conservative estimate of the team's capacity to coordinate information and expertise when handling exceptions.

V. THE MARS LANDER AND ROVER DESIGN PROJECT

a. *The Design Team*

The study involved direct observations of the Next Generation Payload Development Team (NPDT) [12]. NPDT is an intact, multi-disciplinary design team at the Jet Propulsion Lab (JPL) that provides internal JPL customers with state-of-the-art concurrent design and analysis support during the early conceptual design phase of a project. In the current case, an internal JPL customer asked the team to develop science mission concepts and supporting hardware designs that would demonstrate application of a high-power (3 kW) source in future Mars missions.

Participants included fifteen team members and two customers. The majority of the team members were engineers who reported to various engineering and science divisions within JPL. Three of the team members were from external organizations (two from National Laboratories and one from a private firm). External team members provided specialized expertise in design, operation and testing of compact power systems. This particular expertise was needed for the current project in order to address the customers' interest in having the team define mission concepts and hardware designs that would demonstrate application of a compact power system for extended Mars missions. All three of the external team members met with the team and the customers in an initial face-to-face meeting that occurred prior to the team's first "working" concurrent design session. After that initial meeting, all three external members participated in the concurrent sessions from remote locations.

The design team was staffed for the current project with one primary domain expert representing each of seven technical subsystems. These subsystem experts provided design coverage in key areas relevant to space mission design including: (1) telecommunications, (2) power simulation and analysis, (3) avionics, (4) thermal modeling, (5) mechanical CAD¹ and structural design, (6) orbital analysis, and (7) optical instrumentation.

Two other JPL team members included the "systems chair" and the "documentarian." The systems chair was responsible for capturing and

tracking the state of the emerging design, which was recorded in terms of specific assumptions and parameter values that were defined or updated in each of the concurrent design sessions. The documentarian was responsible for taking notes and recording "action items" that emerged in each design session. Action items were typically information retrieval tasks that the team leader allocated to certain team members for off-line processing (between sessions).

The team also had a team leader. The team leader in the studied project was also the individual that developed and implemented the NPDT concurrent design process at JPL [12]. The team leader was an expert in space systems engineering, with knowledge in each of the subsystem domains. The team leader also had systems-level knowledge about the information interdependencies between the various subsystems that needed to be coordinated in order to define a mission. In each session the team leader facilitated coordination of information between the various subsystem experts, the external experts and the customer.

The team had two customers: an internal JPL customer and an external customer. The internal JPL customer reported to a division responsible for Mars missions and systems architecture. The external customer was a member of a Federally-funded Research and Development Center (FFDRC). The JPL customer attended all seven sessions and participated as a full-fledge team member. The other customer met with the team in the initial face-to-face meeting, and afterwards joined most of the sessions as a remote participant.

b. *The Design Process*

The team's concurrent design sessions were held in JPL's Center for Space Mission Architecture and Design (CSMAD), which JPL created in the late 1990s to support system-level design of space missions in a concurrent engineering team environment. The CSMAD facility housed several client computer terminals, which were connected to a main server, and provided team members with access to the Web, the JPL Intranet and design and analyses tools that were used in the concurrent design sessions. In addition, the facility had six computer projection screens, and a systems control terminal that was used to regulate the display of information on the various client terminals and six projection screens contained in the facility (see Figure 1).

In this study, we observed the team developing two separate hardware design concepts: a Mars lander design, and a Mars rover design. The Mars lander design was completed in five, three-hour concurrent design sessions (a total of fifteen hours), over a three-week period. The Mars rover design was completed in two, three-hour concurrent design sessions (a total of six hours), over a one-week period. The current paper reports only on the lander design.

As previously mentioned, the customers for the project were interested in having the team define

¹ In the current project, there was also a junior member of the team who was receiving training from the primary domain expert on use of the team's mechanical CAD tool. The primary domain expert was an expert in structural design and mechanical CAD.



Fig. 1. NPDT team in the Center for Space Mission Architecture and Design (CSMAD) concurrent design facility at JPL.

mission concepts and supporting hardware designs that would demonstrate application of a compact, high-power source for extended Mars missions. Prior to the team's first "working" concurrent design session, the team leader held two trade definition meetings, which focused on clarifying customer requirements and on obtaining early inputs from team members and external experts about relevant mission, environmental and science parameters and constraints. In general, the team leader would use input from these early trade definition meetings to structure a series of "trades," which describes an intense, concurrent engineering design process used at JPL to evaluate and select amongst various design alternatives when defining space missions.

In the early trade definition meetings held for the current project, the team brought in different JPL scientists to speak with the team about specific scientific instruments that were being developed and tested for deployment in future missions. In these discussions, the scientists also provided estimates about the amount of power that would be required to operate certain scientific instruments in remote science operations. The team used this input to weigh the merits of different science mission concepts against the customers' desire to demonstrate application of a 3 kW power source.

As a result of these discussions, it became apparent to the team and the customers that a high power source for future science missions was a new concept for the JPL science community. That is, up to that point, JPL scientists narrowly focused on developing science missions that would jointly satisfy constraints of low power, low mass and low volume. As one JPL astrobiologist indicated to the team:

"If you [let me] increase the power, the first thing I think about is increasing the mass ... but you can't do that. Nobody has thought about what you can do to increase power without increasing mass."

Thus, one of the team's initial trades revolved around defining a science mission that would satisfy the customers' requirement to demonstrate application of a high-power source.

After retrieving and evaluating information from a variety of external experts, the team eventually decided to pursue design of a polar mission using a Cryobot Ice-Penetrating Probe [13]. The Cryobot probe is a scientific instrument capable of

descending through a column of ice, and capturing photographic images and taking measurements of gases and other materials encountered during descent.

After the team selected the Cryobot for the science application, a number of key trades followed. After observing several of the team's concurrent design sessions, it became apparent that trades provided the overall structure around which the majority of the team's design, analyses and information retrieval tasks revolved. In a typical session, team members would provide input to trades based on information retrieved from documents or electronic sources, from external experts, or as a result of completing certain design and analyses tasks. Most of the team's design and analyses tasks were completed in real time within the actual design sessions using high-fidelity design and analyses tools, which team members accessed directly from the CSMAD facility. After completing a particular design, analysis or information retrieval task, a team member would report the results back to the team. Typically, a team member would provide input in the form of a simple verbal report, or by displaying a visual representation, such as a CAD model, spreadsheet, or simulation output, and stepping through the results with the entire team.

One relatively simple trade, for example, involved the team exploring different alternatives for transmitting data between the lander and earth. This particular trade required specific input data, such as the arrival date (of the lander on Mars), and the landing site (on Mars). These data were required by the orbital expert to run an orbital analysis, which would return data on the amount of visibility (and hence, possible data transmission) between the lander, available orbiters, and earth. Using this data, the team was able to select a particular orbiter for the mission. After choosing an orbiter, the telecommunications expert was able to calculate the data transmission rate between the lander and orbiter and earth contingent on the type of antenna selected for transmitting data from the lander; and so forth. Thus, we observed that even simple trades such as this one were highly iterative and involved a complex flow of information between the different subsystems.

After watching the team conduct trades over several sessions, it became apparent that there were different "categories" of trades. One key trade category involved exploring different hardware configurations—what the team leader referred to as "virtual Lego." We observed a particular instance of a configuration trade, which involved alternative sizing and placement of the Cryobot, the package containing the 3 kW power source, a radiator, and various electronic components on the lander. This particular trade spanned a number of sessions and evolved in response to new information that was introduced by the customer and various members of the team.

Throughout this trade, the team jointly created, referenced and modified a number of hardware configuration concepts. This trade relied heavily

on the use of 3-D CAD models, which the mechanical CAD engineer produced in real time within the concurrent design sessions. Throughout this trade, members would verbally describe certain configuration ideas and concepts. The mechanical CAD engineer would quickly translate these verbal descriptions into 3-D CAD models, which were immediately shared with the team. By linking these 3-D CAD models to the trade process, the team seemed to have increased capacity for exploring a larger number of configurations in a relatively short period of time.

c. *The Design Product*

By the end of the team's first set of concurrent design sessions, the team had succeeded in defining a mission and hardware design concept that addressed most of the customers' requirements. The final configuration was represented in a 3D CAD model, which specified the sizing and placement of the Cryobot, the package containing the power system, the radiator, and the separate volumes for the various electronic components on the lander. The team had also tabulated values for the mass, power and dimensions of the various hardware components, and captured additional values for environmental, mission, science and subsystem parameters.

d. *Design Performance*

As previously noted, the lander design took approximately fifteen hours to complete. In this design project, and in other design projects undertaken by this team, the number of design sessions spent on a given design was determined by the budget that the customer allocated to the design effort. Thus, the time allocated to the design effort was an externally imposed constraint. Nonetheless, we were interested in having the customers provide a qualitative assessment of the quality of the team's design relative to the level of effort. To obtain this information, we interviewed the internal JPL customer, and asked him to tell us what elements of the design he felt provided the most value given the purpose of the study. He indicated:

"We identified a really good science mission. I was doubtful when we started. I guess I'm happiest about finding a good mission with a high-power source, and that we're landing where we want to ... Things worked out better than expected."

We also asked the customer to tell us what confidence interval he would assign to the final hardware configuration if the design were carried over into the next phase of the project life cycle. The customer indicated:

"I think the configuration is good. I don't think that's going to change. If we go back and look at this again, the only thing we might do is refine the details of how all the mechanisms fold and go together in a stowed configuration. But I think as a design configuration it's a good one. I'd give it ... say, 90%."

VI. QUALITATIVE METHOD

As pointed out in the previous discussion, trades constituted a central organizing framework for the team's design work. In observing all of the team's trades, we identified a number of key "threads" which reflected design issues that we believed were particularly salient. We selected a particular thread based on our judgment that it satisfied one or more of the following criteria: (1) showed evidence of a significant shift in the team's thinking and/or activities, (2) involved complex interactions between different subsystem domains, (3) involved significant or salient exception discovery and handling processes, or (4) involved multiple information and/or sources of expertise. In addition, we focused on threads that had embedded within them key design decisions that were made by the team over the course of completing the design.

In identifying these threads, our near-term goal was to assess the extent to which different participants would recall the rationale for key design decisions that were embedded in certain threads. Linking back to the research design for the study, my goal was to use transactive memory theory to predict which members would have better (i.e., more accurate and more complex) recall regarding the rationale for key decisions. Transactive memory would predict that subsystem experts would assume responsibility for encoding, storing and retrieving new information items that were encountered by the team if an item fell within a particular subsystem, i.e., was directly related to the team member's particular subsystem. Thus, based on transactive memory theory, we expected the telecommunications expert to recall design decisions that involved data rates, the orbital expert to recall design decisions related to orbital trajectories, and so forth.

In order to test these predictions, we interviewed each of the eleven JPL participants (including the nine team members, the team leader and the internal JPL customer), and asked each to describe the rationale for key design decisions related to the four threads. Each of the four threads contained a key design decision made by the team. These included: (1) selection of a particular Mars landing site, (2) the final hardware configuration on the lander, (3) use of primary batteries during the initial deployment sequence of the mission, and (4) selection of a particular type of UHF antenna for data telecommunications. The first two decisions required input that was broader in scope, i.e., not narrowly focused on a few specific subsystems. Thus, we predicted that for the first two decisions, team member recall would vary more widely since specific participants would assume responsibility for remembering elements of these decisions on bases other than a clear, direct link between the decision and the team member's particular domain of expertise. We did, however, predict the mechanical CAD engineer to have better than average recall for the design decision involving the final hardware configuration on the lander since

this member was responsible for translating team members' concepts into CAD representations.

The third and fourth design decisions revolved around particular subsystems. Thus, we expected members whose subsystems were directly impacted by those design decisions would have better than average recall of the rationale behind those decisions. In the current case, neither the team leader nor the customer was responsible for a specific subsystem. However, both of these individuals demonstrated a strong systems-level perspective on the design. Thus, we expected both of these individuals to have relatively good recall about the rationale behind each of the four design decisions.

VII. PRELIMINARY FINDINGS AND DISCUSSION

Based on these interviews, we found that participants tended to have better recall regarding the rationale for design decisions that were directly related to their particular subsystem, as compared to their level of recall for decisions that were indirectly related or unrelated to their subsystem. The exceptions were the team leader, the customer and the mechanical CAD engineer, all of which generally showed better than average recall of the rationale underlying the various design decisions.

Thus we found that within the context of the current study, transactive memory theory provided a useful basis for predicting how individual team members would attend to and encode new information that was encountered by the team. These preliminary results are consistent with prior transactive memory research, which found that group members remember more information in their own areas of expertise when they think other members have unique versus similar expertise [8]. Our observations suggest, however, that teams where members' expertise is highly differentiated (i.e., unique and non-overlapping) may be more susceptible to information losses or memory "leakages" when information encountered by the team isn't clearly linked to certain members on the basis of members' personal expertise. Indeed, within the current study, we observed exceptions emerge in the team's design work when members assumed that certain team members had taken responsibility for certain information, only to later discover that those team members hadn't encoded the information since it wasn't clear to the members that the information was directly related to their particular subsystem.

Though preliminary, these findings raise questions about what constitutes an "efficient" transactive memory system. The current research suggests that in cases where a group's work is relatively stable, i.e., does not involve an influx or production of a lot of new information, a highly differentiated transactive memory system may be suitable. However, in task situations involving a large volume of new information that is not readily partitioned and allocated according to unique domains, a less differentiated transactive system might be needed for greater information "uptake."

Future work by the authors will address these questions, and other related ones.

ACKNOWLEDGMENT

The authors wish to thank Knut Oxnevad, members of the NPDT, Paul Deflorio and Terence Moran at JPL for their cooperation in this research.

REFERENCES

- [1] C. Christensen, *The Innovator's Dilemma*. Boston, MA: Harvard Business School Press, 1997.
- [2] A. Grove, *Only the Paranoid Survive*. New York, NY: Doubleday, 1996.
- [3] J. C. Kunz, T. R. Christiansen, G. P. Cohen, Y. Jin, and R. E. Levitt, "The virtual design team," *Comm. of the ACM*, 41(11), 1998, pp. 84-91.
- [4] D. M. Wegner, "Transactive memory: a contemporary analysis of the group mind," in *Theories of Group Behavior*, B. Mullen and G. R. Goethals, Eds. New York: Springer-Verlag: 1987, pp. 185-208.
- [5] D. M. Wegner, "A computer network model of human transactive memory," *Social Cognition*, 1, 1995, pp. 319-339.
- [6] Y. Jin and R. Levitt, "The virtual design team: a computational model of project organizations," *J. Computational and Mathematical Organization Theory*, 2(3), 1996, pp. 171-195.
- [7] A. B. Hollingshead, "Distributed knowledge and transactive processes in decision-making groups," *Research on Managing Groups and Teams*, 1, 1998, pp. 105-125.
- [8] A. B. Hollingshead, "Perceptions of expertise and transactive memory in work relationships," *Group Processes and Intergroup Relations*, 3, 2000, pp. 257-267.
- [9] V. Anand, C. C. Manz, and W. H. Glick, "An organizational memory approach to information management," *Acad. Mgmt. Rev.*, 23(4), 1998, pp. 796-809.
- [10] Moreland and L. Myaskovsky, "Exploring the performance benefits of group training: transactive memory or improved communication?" *Org. Behavior and Human Decision Processes*, 82(1), 2000, pp. 117-133.
- [11] D. L. Rulke and D. Rau, "Examining the encoding process of transactive memory in group training," *Acad. Mgmt. Proc.*, 1997, pp. 349-353.
- [12] K. I. Oxnevad, "The NPDT- The next generation concurrent design approach," *Proc. European Systems Engr. Conf. (EuSEC)*, Sept. 13-15, Munich, Germany, 2000, pp. 303-306.
- [13] Jet Propulsion Lab, Cryobot Ice-Penetrating Probe [Online], Available: http://www.jpl.nasa.gov/technology/images_vi_deos/iv_pages/mars-cryobot1.html [Accessed 5 June 2002].