Observation, Theory, and Simulation of Integrated Concurrent Engineering:
Grounded Theoretical Factors and Risk Analysis Using Formal Models

By

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OBSERVATION, THEORY, AND SIMULATION

OF

INTEGRATED CONCURRENT ENGINEERING:

GROUNDED THEORETICAL FACTORS

AND RISK ANALYSIS USING FORMAL MODELS

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ABSTRACT

Since 1996, NASA's Jet Propulsion Laboratory (JPL) has designed space missions at a vastly accelerated pace using *Integrated Concurrent Engineering* (ICE). I observe that ICE leverages distinctive product, organization, and process elements such as networked information technologies, advance selection of participants who span interdependent fields, and a superficially chaotic work environment. A mainstream thread of organizational theory, illuminated by computational models, supports ICE performance claims. But it offers insufficient intuition to organizational designers about how ICE works and sheds no light on the conditions under which it can be replicated in other design domains. To extend this theory, I assert that ICE teams at JPL manage ten enabling factors that lead to exceptionally low information response latency, and consequently to a dramatic improvement in project duration over traditional methods. I propose response latency as both a unifying theoretical principle and a practical metric that can describe, evaluate and manage engineering design collaboration. Project managers should establish the specific, measurable objective of very short latency as a project design principle. Project managers who want to implement ICE for their own use should set the goal of reducing it to near-zero with careful attention to average and worst-case coordination and exception handling latency, but without undue concern for practices targeting best cases. Improving the likelihood that engineers have the information or decisions that they need as soon as they need it allows ICE stations to move forward at a greatly accelerated, synchronized pace. A carefully designed network of knowledgeable and collectively independent participants, along with rapid, precise, and semantically rich communication of design intent, choices, and predictions, are two other features of the ICE approach that shrink response latency to near zero. ICE can be viewed as the "Just in Time" approach to knowledge work, in that it supplies four simultaneous information flows with infinitesimal latency ("lead time") and high micro-scale reliability ("service level").

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INTRODUCTION

DESIGN TEAM PERFORMANCE

Integrated Concurrent Engineering (ICE) achieves extraordinarily rapid design with a quality similar to or surpassing traditional methods and a lower cost. I find that ICE uses: a singularly rapid combination of expert designers; advanced modeling, visualization and analysis tools; a set of consistent social processes, and a specialized design facility; to create preliminary designs for complex systems. When compared with a traditional parallel engineering method, successful ICE users reduce project schedule by several orders of magnitude, while substantially improving design cost and maintaining quality standards. Today's pioneers of ICE are in the aerospace and automotive industries, where several closely related methods are termed "ICE", "Extreme Collaboration", 'Concurrent Design Engineering", or "Radical Collocation" [Mark 2002, Benjamin and Pate'-Cornell 2004, Covi et al 1998, Olson et al 1998]. Whereas traditional engineering superficially resembles a government bureaucracy, ICE performs the same work in an environment more akin to NASA's Shuttle Mission Control operations.

Our research is based primarily on the most experienced ICE team at NASA, the Jet Propulsion Laboratory (JPL) Advanced Project Development Team, conventionally known as Team-X[1]. Team-X completes early-phase design projects in

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[1] With thanks, but without explicit description, we leverage observations from similar practices at the Tactical Planning Center at Sea-Land Service Inc., and at

less than one-tenth the time of the previous process at JPL, and for less than one third of the variable cost. Although there is continuing effort to improve the quality of the Team-X designs and the generality of their method, the Team-X product is good enough that outside investigators choose to purchase Team-X services about fifty times a year. The team is in heavy demand in the competitive market for mission design services, and its successful plans have brought hundreds of millions of dollars in business to JPL and its suppliers [Sercel 1998].

AN ILLUSTRATIVE METAPHOR

I find that an auto metaphor conveys our intuition that, in spite of superficial differences, ICE differs mechanistically from standard design principally in that it operates more rapidly. Metaphorically, I conceive of ICE as analogous to the operation of high-performance race cars in that ICE engages the same considerations as standard design teams, but like the race car, many elements of the total system are customized for high performance. The race car has specialized engine, transmission, tires and even a racetrack. Analogously, ICE requires expert selection and preparation for participants, the organization, the enabling modeling and visualization methods, and the design process the participants follow. For the racecar, any bump in the road, hardly noticeable at twenty miles per hour, can be disastrous at two hundred. Therefore, before a race, the track must be cleared and leveled. Analogously, the Team-X "pre-session" structures the tasks, and chooses the participants and the variables of interest for the project at hand. Finally, once the race starts, the driver

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Stanford's Real-Time Venture Design Laboratory, Gravity Probe B Mission Control, and Center for Integrated Facility Engineering.

responds principally by reflex, in accordance with training and experience, because there is little time for deliberation. An ICE team must also work quickly to do its design and make decisions quickly, conclusively and well. Our intuition is that the race car and the ICE team are structurally identical to the standard car and design team; the fundamental forces and operations in play are the same in both cases; and those specialized, enabling adaptations of a generic design result in the radically different performance in both cases. Thus, while operating at high speed (low latency), I am still looking at a car (or a multi-disciplinary design project), and I can understand it by understanding the behavior of the fundamental mechanisms in a car.

This "Systems" perspective suggests that an ICE implementation that lacks a single critical aspect may result in unimproved performance, or even project failure. In our analogy, an otherwise optimized race car with an ordinary engine cannot generate enough power to compete; and placing an ordinary driver behind the wheel would be catastrophic. Furthermore, factors that are irrelevant under some conditions may become important in others. These factors offer a key to understanding novel phenomena such as ICE. Wind resistance, for example, is of no consequence at low speeds, but it motivates streamlining at high speeds. A truly novel enhancement, wings, converts the once detrimental wind resistance into beneficial lift, and revolutionizes transportation.

GOALS OF THIS RESEARCH

Although this paper does not determine whether ICE is revolutionary, our observations, theories, and simulations address the theorists' questions of *how, why, and in what ways ICE works.* Most early descriptions of ICE are anecdotal, motivational, or limited in perspective, rather than being grounded rigorously in broadly validated theory. Recent research on the behavior of ICE and similar projects [Mark 2002, Teasley et al 2000] describes the features of ICE, namely that it is highly concurrent design by multiple collocated multi-disciplinary experts. But the academic literature stops short of explaining the fundamental mechanisms of ICE and its behavior.

Our theoretical results suggest methods by which an important range of applications can adopt ICE in its entirety. Of equal importance, they articulate reasons why most organizations may find moving to ICE extremely challenging in the short term. For practical organizational designers, I identify a process performance metric that can help teams understand the limits on their performance today, and that provides a focus of attention that can significantly improve their effectiveness in any kind of collaboration.

OUR METHODOLOGY

This research had three orthogonal and complementary research elements: *observations* of a radically accelerated project at JPL, *development of formal yet intuitive theories* that have face validity and offer a straightforward comparison with established social science theories, and *computational simulation* whose predictions show the emergent implications of foundational micro-theories at the project-level. Our claims are based on simultaneously *validating* theories by comparing them with observations, *verifying* theories' consistent operationalization in a simulation model, and *calibrating* the results' implications against our initial and new observations. Our work is therefore explicitly grounded by consistencies among reality, intuition, and formal modeling and simulation.

Observation

I visited JPL's Team-X and ethnographically observed three design sessions of a sample project. In several hours of on-site interviews, I collected quantitative and qualitative details about the participating organization, process, and culture. Finally, after coding and analyzing this information, I followed up with an online survey covering the amount of time each participant spent in direct work, communication, and rework each week. I describe the ICE practice in detail, and propose *information response latency* as a fundamental, observable process performance measure.

Theory

Our observations, interviews, and survey ground a set of factors that enable radical project acceleration. I explain ten fundamental mechanisms that work together to keep response latency at a minimum, and, thereby, allow projects to execute at a very high speed. Although I leverage existing literature extensively, my theorizing also draws on novel behaviors and relationships observed in ICE practice.

Simulation

I apply three computational project models to describe and predict the performance of an ICE team. I retrospectively calibrated the Organizational Consultant (OrgCon), Virtual Design Team (VDT), and Interaction Value Analysis (IVA) models to describe our observations at Team-X accurately, and found that that they are able to predict observed ICE phenomena with considerable fidelity. I conclude with an analysis using a detailed VDT model that supports our enabling factor theories.

THE ICE METHOD OF DESIGN AT NASA/JPL

Figure 1: Team-X Photograph The JPL Product Development Center hosts co-located, cross-functional designers, each with a unique specialty, and each having a modeling and simulation workstation. The projection screens can display any workstation's data. A working environment that supports efficient networking is necessary, but not sufficient for them to be successful. Photograph courtesy of NASA/JPL/Caltech.

In hundreds of projects since 1996, Team-X has developed and applied ICE in short design sessions. Figure 1 shows a design session in the custom Product Design Center facility. Team-X projects develop initial unmanned, deep space mission designs so that they can be evaluated for funding[2]. Team-X works in a market economy; there is no requirement to use it. NASA principal investigators have alternative ways to develop designs, and over nearly a decade, on hundreds of occasions they have chosen to employ Team-X. A normal product of a Team-X session is a proposal, and successful proposals have brought JPL a large and sustained volume of mission work. Figure 2 illustrates the Team-X product, organization, and process elements.

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[2] At NASA, this work is known as "Pre-Phase-A" or "Advanced Studies". It precedes Preliminary Analysis, Definition, Design, Development, and Operations [NASA 1995].

JPL founded Team-X in the mid 1990s, primarily in response to NASA's "faster, better, cheaper" directive and the availability of Business Process Reengineering (BPR) methods [Smith 1997, 1998; Smith and Koenig 1998; Wall 1999, 2000; Wall et al 1999, Hammer and Champy 1993]. Recently JPL created two additional ICE teams (Team-I for scientific instrumentation and Team-G for ground systems design), and NASA developed a similar group at the Goddard Space Flight Center.

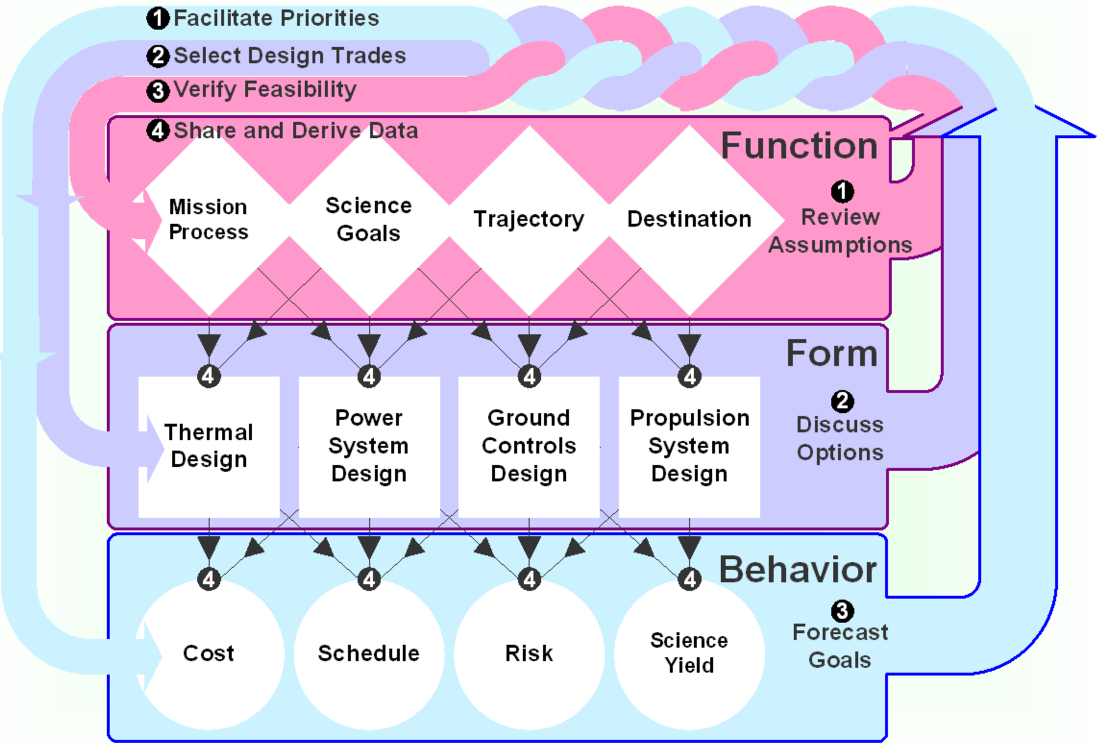
PRODUCT

Team-X designs the initial, technical design core for an unmanned, deep space mission proposal. The three horizontal areas in Figure 2 illustrate our decomposition of this work into three components: a mission *function*, an engineering design *form*, and a predicted *behavior*. The function, or mission purpose, includes a choice of destination, travel trajectory, scientific goals, and proposal limits such as launch deadline, budget, and risk posture. These elements drive the form of a mission's major engineering and organizational system designs, such as thermal, power, ground controls, and propulsion. The final proposal also includes a detailed analysis of the anticipated behavior of the mission, in cost, schedule, risk, and scientific yield.

ORGANIZATION

Team-X includes about eighteen domain experts, a facilitator, and a customer representative. Each of the engineer "chairs" is responsible for design decisions within a specific domain "station" such as Power, Propulsion, Cost Estimation, or Trajectory Visualization. Each chair principally directs the mission function, designs its form, or predicts its behavior, as Figure 2 illustrates with the arrangement of white boxes. Projects of limited scope forego unnecessary stations' participation, and Team-X develops new stations (such as Risk Analysis) to meet changing demands.

Figure 2 Team-X Schematic Each Team-X "Chair" engineers a component of mission function, design form, or anticipated project behavior. They coordinate using four interdependent processes: Facilitator-mediated tracking of design conformance to goals; "Sidebar" agreements on design trades; Functional review of goal feasibility; and automated data sharing of networked spreadsheets.



Whereas most engineering teams of this size employ a multilevel management hierarchy, Team-X is a much more flat and broad organization. The team’s facilitator focuses group attention on particular issues, may suggest “sidebar” conversations in which several discipline specialists resolve an issue of shared interest, and directs attention of individuals and the group to newly emerging information. A customer representative has the final authority on decisions that impact the achievement of the project’s scientific goals.

Team members are selected for their technical competence, their experience, and their independent ability to work effectively in the informal, superficially chaotic, high-pressure conditions. Partly because they are so psychologically demanding, Team-X limits design sessions to three hours. After an eight-hour ICE charrette demonstrating Virtual Design and Construction at Stanford, one participant felt as if he had been “run over by a train” [Garcia et al 2003].

PROCESS

A typical Team-X project requires fewer than five hundred full-time-equivalent hours, spread over a four-week period. Team-X does not attempt to perform its entire project analysis under Integrated Concurrent Engineering. Rather, in the first, “pre-session” week, certain select engineers pin down the scientific requirements and mission design with a customer representative. During the second week, the team meets for three intensive “design sessions” of ICE, each lasting three hours. In the two weeks following the design sessions, the team typically finalizes and documents the design in a more traditional, distributed fashion.

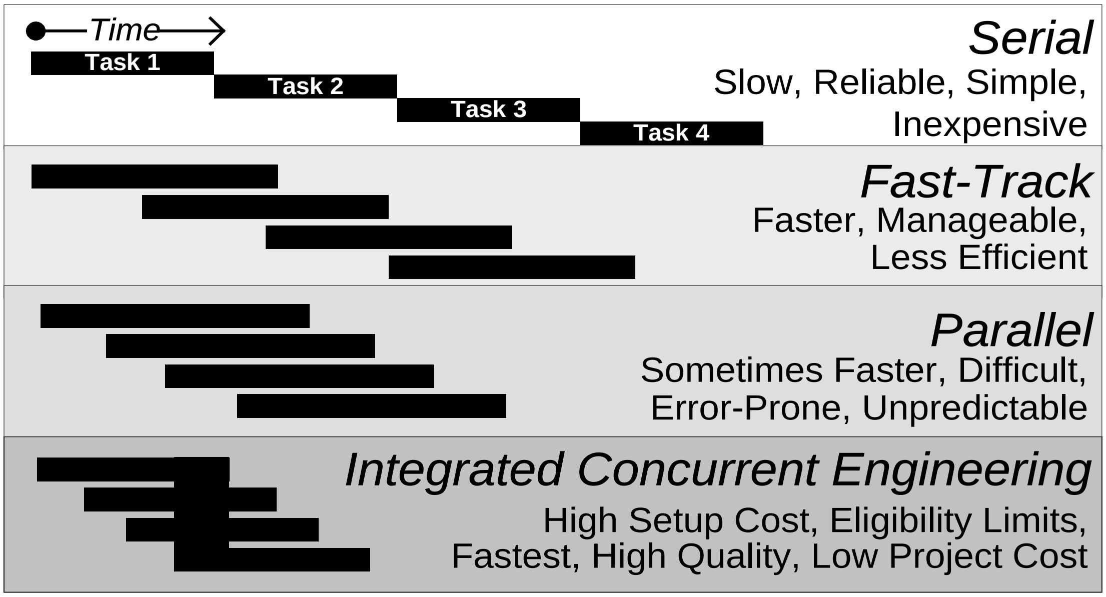


Figure 3 Degrees of Parallelism This diagram shows four tasks arranged with increasing parallelism. Projects under increasing pressure to meet tight schedules often overlap tasks that were once completed serially. Compressing schedule in this way is costly, difficult, and places increased risk on the product, organization and process. ICE represents the most accelerated of project designs.

The ICE design sessions consist of informally coordinated, but highly focused, simultaneous development of interdependent material by all team members. The sessions resemble traditional meetings in that a designated facilitator communicates the agenda and monitors the session's progress. However, in ICE the participants continuously form and dissolve "sidebar" conversations to share information or solve emergent problems. The physical orientation and movement of engineers in the room passively communicates the structure of many such conversations to the entire group. Participants have also been known to overhear errors and instigate their correction [Mark 2002], although a rough simulator evaluation of this phenomenon's performance impact by [Bellamine and Saoud 2002] was inconclusive. Even though the engineers represent several organizational divisions, there are no managers present in the design session. Instead, a single facilitator helps sidebars to form, and directs the group's attention to important developments.

Figure 3 illustrates the differences in timing of subtasks between ICE and traditional process. Whereas ICE participants are fully dedicated to a particular project for the duration of the session, engineers using the traditional process are often involved in more than one project at a time. Traditional projects use substantially more management oversight, and rely more on technical experts who are not fully dedicated to the project.

TOOLS AND FACILITIES

Each design participant has a computer workstation and a set of discipline-specific modeling, visualization and analysis tools. The team has a shared database (called ICEMaker) with which each workstation has a networked publish-and-subscribe connection. The ICEMaker database has a generic data schema of nearly four thousand design variables that represent the functional requirements, design choices and predictions of each discipline. Computer systems and facilities personnel support the group's tasks without actively influencing the designs themselves.

ICE projects often occur in dedicated facilities and employ high-performance computer modeling and simulation tools, large interactive graphic displays, remote collaboration systems, and a mature shared generic project model that the design team instantiates for the project. For example, interdependencies and constraints across disciplines are explicit and agreed upon.

The Team-X facilitator monitors the collective design verbally and though an information technology infrastructure that is characteristic of the ICE method. Three large screens cover one wall and typically monitor top-level design conformance measures (such as cost, mass, and volume), the mission trajectory, and the designed vehicle's physical configuration. Each domain representative runs a networked spreadsheet model that communicates the design choices currently being considered. A facilitator, a laptop-toting customer representative, and a speakerphone typically occupy the only table without dedicated monitors.

More specifically, every member of Team-X uses a spreadsheet that his or her organization has established explicitly for the task. ICE requires the engineer and spreadsheet to encapsulate much of the invariant data and procedural knowledge that is required during design sessions.

ORIGINS

Integrated Concurrent Engineering or ICE, results from a successful application of *business process re-engineering* (BPR) to highly interdependent engineering tasks that today are more commonly performed in parallel using traditional methods. Because of the complexities of matching product, organization, process, and tools, BPR efforts frequently overrun budget and, once complete, often fail to meet expectations. For this reason, practitioners and consultants are generally eager to learn what they can from successful BPR applications, such as ICE.

Today, many industries experience dramatic increases in the volume and intensity of competition. Simultaneously with high-level strategies such as the globalization of operations, firms look for ways improve existing operation using new technologies and work practices. Principal among these developments are computing and communications technologies, and corporate re-organization or downsizing.

In the early 1990s, Hammer and Champy defined a powerful synthesis of these concepts [Hammer and Champy 1993]. The authors explained that most firms experience change gradually, and their organizations and work methods, or processes, adapt gradually. Business operations naturally retain some adaptations that were evolved or designed for conditions that no longer exist[3], and it eventually becomes easier to replace the work methods entirely than to attempt to fix them incrementally. This "Business process re-engineering" or "BPR" procedure uses information technologies to enable completely new work practices that bear little resemblance to those previously in place. In the 1990s, BPR consulting became a multibillion-dollar industry, and its dramatic improvements to efficiency are often credited, together with information technology, with stimulating the economic boom of the late 1990s.

In many industries, highly interdependent work practices have adapted by partially overlapping previously serial tasks. For example, whereas it once sufficed to complete a building's framing before installing the electrical system, it is now routine for construction firms to begin the latter task as soon as the first areas are framed in. Overlapping dependent tasks adds complexity, however, because the results of work that would traditionally have been complete may be unavailable or subject to changes. Scheduling too much parallelism can be counterproductive and risky.

FOUNDATIONS OF DESIGN PROJECT ANALYSIS

Inspired by ICE's novelty and differences from traditional design approaches, I explicitly assess the practice's amenability to previously established organizational

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[3] While mostly uncontroversial in the professional literature, some evolutionary organizational theorists debate this phenomenon under the heading of "path dependence" [Scott 1998].

theories. Although it does not tell the whole story, existing theoretical research on organizations offers a point of departure for our exploration of parallel engineering teams' work and structure. At the project level, I find that traditional organization theories are applicable and insightful, while at a more detailed level, I find that important questions remain. In this section, I synthesize established organizational theories into a foundational framework that accommodates both ICE and traditional practice. I instigate and terminate this process by comparing observed ICE behavior against the predictions of theoretically and empirically grounded computational models.

AN ORGCON MODEL OF ICE

I began our analysis using a computer program that is firmly rooted in a range of established organization contingency theories. The Organizational Consultant, or OrgCon, is a rule-based expert system that Richard Burton and Børge Obel developed and documented in their 2004 book, *Strategic Organizational Diagnosis and Design (3rd edition)*. When provided with values for a set of contingency variables such as structure and environment, this system predicts an organization's potential weaknesses in terms of mismatches between its strategy, structure, climate, management style, and other factors. OrgCon typically assesses the strengths and weaknesses of whole companies' organizational structures, although it is also able to analyze subsidiaries or other organizational subunits.

I applied OrgCon to a hypothetical company that conducts the majority of its business as I observed Team-X to do. In response, OrgCon predicted a striking range of distinctive aspects of Team-X operations, such as:

> *…Coordination and control should be obtained through integrators and group meetings. The richness of the media should be high with a large amount of information. An open organizational climate and team spirit must be fostered. Information must be shared among all levels. Constructive conflict on "what to do" will be usual. Individual tolerance of ambiguity and uncertainty will be necessary. Mutual adjustments of "give and take" will be the norm. Frequent informal meetings and temporary task forces will be the primary coordinating devices…*
>
> \- *OrgCon*

I provided none of the information in this diagnosis as input, and yet OrgCon returned specific and strikingly accurate descriptions of JPL design sessions' tools, people and process. Theory, model, and professional practice validate one another, for example, in that the system's "Frequent informal meetings and temporary task forces" prediction accurately describes both Galbraith's theoretical recommendations [1973] and the observed Team-X sidebars (I explore the importance of this and other features, such as "Ambiguity", "Richness of the media", and "Team spirit" later in this paper). The OrgCon report lends confidence in the computer model's applicability, and demonstrates that existing organization theory and diagnostic tools can predict elements of ICE's success.

By predicting no major shortcomings (known as "misfits" in OrgCon) for the ICE approach, OrgCon raises the exciting possibility that ICE is a new, distinct and effective organizational form. Many organizational researchers (notably Mintzberg [1980], along with Burton and Obel**)** hypothesize that only a handful — typically five or six — of internally aligned archetypal organizational configurations exist that are well adapted for specific combinations of the contingency variables. OrgCon is not single-handedly equipped to assess such a claim, but it does provide a degree of confidence, complementary to empirical claims, that ICE is both effective and sustainable. Because OrgCon does not offer positive, clear and compelling evidence of ICE's effectiveness, however, I cannot conclusively determine whether an important gap in theory, observed practice, or model is present from this analysis. I therefore turn to a selection of prominent and more operationally explicit theories to assess in detail the extent to which social science theory encompasses ICE behavior.

INFORMATION PROCESSING VIEW

Galbraith (1973) argues that the primary function of organizations is the processing of information. Shortcomings in information flow or knowledge in an organization produce "exception" events that require managerial attention. I interpret exceptions as perceived faults or gaps in the decision basis that disallow "clarity of action" [Howard 1992, Howard and Matheson 1993]. Organizations route the information or queries that are pertinent to these exceptions to complementary resources, such as management or peers. Organizations, according to Galbraith, are designed primarily to route and process information and to handle exceptions as efficiently as possible.

This "information processing view" predicts that the match between workers' capabilities and their tasks determines the necessary tightness of intra- and inter-organizational collaboration. For example, Galbraith conjectures that organizations may form temporary, interdisciplinary task forces when a large number of interdependent issues arise. Although Team-X is not a temporary organization, it operates like a task force that is formed to address a single phase in each of several larger projects. At a lower temporal and organizational level of abstraction the ICE sessions' sidebar conversations, which operate like internal task forces, form and dissolve continually. Our analysis of ICE shows that the former, team-scale information processing view of exception handling motivates the formation of Team-X, while the latter, individual-scale demands of individual communications drive the group's structure and information technology configuration. After further developing the theoretical foundation, I return to this point under "ICE Enabling Factors".

DIRECT WORK

I view engineering projects as consisting of many interrelated design decisions. The institutional branch of organizational theory indicates that people make decisions and select procedures using a sense of personal identity and a "logic of appropriateness" [Powell and DeMaggio 1991, March 1994, Scott 1998]. ICE decision support technologies, engineering culture and public decision making processes strongly encourage formal and impartial evaluation of design alternatives. This conformity to a "Rational" normative identity leads us to adopt a *general rational framework* model [March 1994] of decision making in the tightly knit ICE team.

According to formal rational decision theories [von Neumann and Morgenstern 1944, March 1994], individuals make decisions by combining four elements: beliefs, preferences, alternatives, and a decision rule. Alternatives are possible actions (including passiveness) among which a decision-maker must choose. Beliefs are matters of fact or expectation about history, the current world state, and the possible future consequences of alternative actions. Preferences are personal measures of relative desirability among specific future prospects that might result from the selection of an alternative. The last element, a decision rule, is a method for determining which among several alternatives should be acted upon, for a given set of beliefs and preferences.

Economics and probabilistic decision and risk analysis are based on a “Rational” ideal, which uses the “Maximization of expected utility” decision rule [Lave and March 1975, Luce and Raiffa 1957, 1990]. According to the “bounded rationality” thread of organizational theory, sparked by March and Simon [Simon 1997, March and Simon 1958], individuals are cognitively and contextually unable to make fully rational decisions. Instead, organizations accommodate and compensate for individuals’ limitations, so that coordinated behavior can approach rationality.[4]

A VDT MODEL OF HIDDEN WORK

Project managers frequently underestimate the emergent workloads of subordinates whose work is highly interdependent, in part because coordination efforts are not explicit in traditional planning and schedule tracking systems. Jin and Levitt (1996) use the term “hidden work” to describe coordination and exception handling efforts that produce a substantial fraction of the total labor and schedule pressures in complex projects that combine high levels of task interdependency with significant levels of parallelism. Overloaded workers sometimes fail to respond to communications, thereby compounding the information supply problem and compromising others’ performance. Complexity and interdependence thus results not simply in additional direct and communication requirements, but also triggers new exceptions and errors.

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[4] Prospect theory [Tversky and Kahneman 1974] observes that people respond to decisions’ contexts, even when they do not impact the traditional decision basis elements. Because we do not calculate the engineers’ specific choices, we safely address this framing principally as part of the decision rule.

Knowledge of this phenomenon forms the basis of many experienced analysts' skepticism toward ICE performances claims.

The Virtual Design Team simulation system (VDT) is currently the most complete computational model of hidden work in project teams. For a detailed description of VDT mechanics, see [Jin and Levitt 1996]. I have encoded the results of our observations and interviews at JPL in a VDT model of ICE, and found that some, but not all of the simulation's retrospective predictions match the results of a follow-on survey.

I offer a micro-level view of information processing on the four elements of the decision basis. Engineering agents routinely make decisions in which the amount of information, range of preferences, work procedure (decision rule) and number of alternatives vary. Our analysis views focused, uneventful work as consisting of sequences of straightforward decisions. In less routine work, agents occasionally encounter decisions for which elements of the decision basis are inadequate, unavailable, or incorrect.

EXCEPTION HANDLING

Organizational agents are not generally aware of all the nuances of an organization's strategic intent and goals. Similarly, workers will sometimes find that their technical expertise is insufficient to finalize a work element. The VDT system models perceived technical inadequacy and ignorance of organizational preferences as exceptions (potential errors) that management must contemplate and, perhaps, order to be reworked. In the model, they emerge probabilistically during work, with a frequency based on task complexity measures, as well as on the adequacy of the assigned agent's experience and skills relative to the task requirements. The VDT model represents project exception handling as involving an upward flow of exception handling requests and a downward flow of *rework*, *quick fix*, or *no action* choices along one or two fixed exception handling hierarchies (project hierarchy only, or both project and functional hierarchies in a matrix structure). Management is the clear authority on organizational preferences, and also — in traditional organizations — the repository of superior technical knowledge. Thus, the hierarchical VDT exception-handling model captures a micro-organizational adaptation to uncertainty about preferences upon which to base decisions and components of decision rules.

Exception handling can produce a large fraction of a task's total work volume, especially for technically challenging or equivocal projects. Moreover, when a supervisor oversees many agents, each of whom has complex tasks that are being performed in parallel, the supervisor's exception handling workload may become unmanageable. This backlog can result in a failure to review the exceptions properly, causing a ripple effect of problems extending through all of the manager's subordinates.

INFORMATION EXCHANGE

Some decisions require information that does not simply reside among management, but that a previous or parallel work task creates during the project. Such information may impact the range of available design alternatives (as with design configuration interdependence), or they may influence the predicted results for a given choice. Accordingly, VDT agents request information from others that are engaged in interdependent work (at a rate that is based on agent skill, prior team experience, and task uncertainty). In this situation, the simulator routes a virtual information request and possible reply between the agents. Because this process supplies agents with data produced by other tasks, and this data influences the range and significance of design options, I view the VDT communications model as capturing a micro-organizational adaptation to gaps in designers’ understanding of management preferences, and gaps in knowledge about how to make certain decisions.

When an agent performs a task that has a very large number of interdependencies, the time spent in communications may actually exceed the amount of direct work task. If the workload becomes unmanageable, quality may degrade significantly- not just for the principal task, but also for related tasks that either rely upon the task’s output, or that must be coordinated with the given task because their subgoals interact.

REWORK AND DESIGN ITERATION

In addition to direct, heads-down work, coordination time such as information exchange and meetings, and decision waiting time, VDT calculates the predicted volume and distribution of rework. Rework results from handling exceptions conservatively, and consists of performing a task (or subtask) a second time. Conventional project analysis considers rework to be a measure of inefficiency, even in contexts where its complete elimination is not feasible.

Engineering typically involves repeatedly designing a product, evaluating it against fitness metrics, and redesigning it according to the results. For example, an initial mission design might require a higher budget than is available. In this case, engineers proceed to construct a second design, based on lessons learned from the first, with a greater focus on lowering costs. This “Design iteration” process enables an engineering team to explore a range of possible designs, and is an integral part of a project plan. An engineer who builds the same design twice because of file corruption indicates wasteful rework, while another who considers a second way of building a component is performing valuable design iteration.

Space mission design involves simultaneously iterating among many designs in each of many highly interdependent engineering tasks. If an ICE station is unaware of changes to a design element on which it depends, it risks building an incompatible design. This constitutes rework, in that the effort is invalid and wasteful. If the ICE station is aware of the change, then constructive, valuable new design iteration will ensue.

An effective ICE session includes a large work volume of design iteration, and a low volume of rework. VDT does not distinguish between rework and unscheduled design iteration, simulating exception handling for both in the same way.

SIMULATING TEAM-X USING VDT

To build a VDT project model of Team-X, I created 15 VDT agents to represent Team-X engineering stations, as well as a facilitator and proposal manager, and I provided each with an individualized task. In a series of interviews, Team-X participants supplied the tasks' complexities, work volumes, start times, and rework and information exchange networks. Simulating the model showed the predicted results of all the agents working, exchanging information, and handling exceptions.

Figure 4 compares an average number of work hours per VDT station agent, by type of work task and according to a number of sources. Prior to project start, all Team-X participants requested a time budget to do their work, which I averaged as the rightmost Work Authorization Memo (WAM) value. The Survey column reports the data ICE participants provided after project completion. I retrospectively calibrated the VDT simulation to predict the total work volume for each project task as well as the direct work, coordination, rework, and time wasted waiting for exception management. The averages of these values appear in the leftmost, Baseline VDT column.

Figure 4 illustrates that using input data collected at JPL (including work volumes reported retrospectively by Team-X) I was able to calibrate VDT to produce emergent behavior that matches an actual Team-X project. This suggests that at an aggregate level, a properly calibrated VDT model can retrospectively predict the volume and

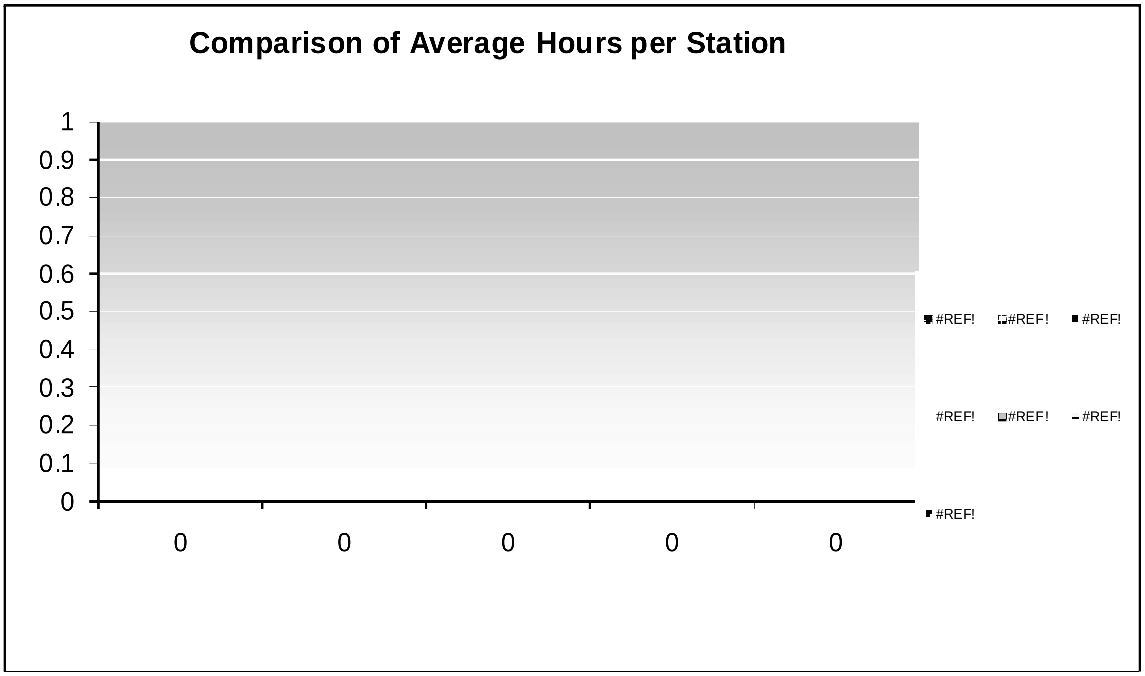

Figure 4: Comparison of work volumes on a sample JPL Team-X project from various sources. The columns represent (from right to left) reported, predicted, surveyed, simplified/simulated, and retrospectively simulated data. At a high level, there is agreement among them.

distribution of direct and hidden work for this type of project. Founded in a model-based interpretation of information processing theory, this result qualitatively cross-validates the heuristic body of theory Burton operationalizes in OrgCon, ethnographic ICE observations, and the VDT computational model I developed using interviews and surveys.

ANALYSIS OF ICE RISKS

PERFORMANCE ANALYSIS AND RISK

VDT provides a range of organization, and process performance measures, including emergent work volumes, a project schedule, and coordination rates. Our calibrated simulation of nominal Team-X operations found outcome measures each to fall at a qualitatively acceptable level, but to vary in theoretically significant ways. I interpret the VDT outcomes as measures of risk to the mission design product, the Team-X organization, and the conceptual design process.

VDT uses a Monte Carlo simulation, but inputs qualitative and quantitative project design parameter values and project structure, calculating irreducible, probabilistic distributions of outcome variables. Specifically, the system describes outcome measure distributions using average results and variances. For example, VDT does not predict a single quantity of information exchange requests, but instead states a simulated average and standard deviation.

Furthermore, VDT does not attempt to model agents' midstream monitoring of, and intervention in the configuration of the project organization or work process. Instead, the system predicts the behavior that would develop if the organization and process were to proceed as initially designed. Intuitive management interventions can be effective, but they can also be counterproductive. For example, real managers would likely observe the developing problems and attempt to intervene in a delayed project by hiring additional new workers, whereas a VDT analysis might indicate that doing this would further extend the schedule (Hiring additional workers under these circumstances frequently extends a project's schedule, rather than reducing it [Brooks 1995]).

Because VDT predicts likely outcomes, not psychologically or socially certain outcomes, I interpret the system's performance measures to characterize the degrees of *risk* associated with different project aspects. For example, when a project shows high cost risk, large cost overruns are likely unless management responds with proportionally effective interventions.

PRODUCT RISK

The product of a Team-X ICE project is a set of complementary design choices that form the basis of a mission. I use the term *product risk* to describe the likelihood that design choices are fundamentally invalid or inconsistent. Product risk is important because it may lead to an improper decision about whether to proceed with a mission, or to a mission that is needlessly costly, risky, or extended in schedule.

In this paper, I do not consider the cost, quality, or schedule of planned missions, however, I do use VDT predicted project behaviors to predict the likely accuracy and completeness of the team's own analysis of these factors. Team-X requires appropriate stations as well as an effective collaborative process to correctly estimate the mission's programmatic risk, costs and schedule. Benjamin and Pate-Cornell highlight the need for probabilistic risk analysis in this project setting [2004], and

Team-X's new Risk Station testifies to its perceived importance at JPL [Meshkat and Oberto 2004]. Our analysis of product risk is distinct from, and complimentary to such approaches.

Our analysis highlights the impact of organizational risk factors on process quality because they are estimated to contribute to 50-75% of major modern catastrophes [Paté-Cornell 1990, Murphy and Paté-Cornell 1996]. For descriptions of over a hundred organizational risk factors, and related literature reviews, see Ciavarelli [2003] or Cooke, Gorman and Pedersen [2002]. Important factors that VDT does not evaluate include conformity, which decreases the likelihood that individuals will contradict peers' public, erroneous statements [Festinger 1954]. "Groupthink", reduces the likelihood of thorough, critical evaluation of alternatives in a group setting [Janis 1982.2]. Finally, the "Risky shift" phenomenon leads groups to select choices that are more risky than those which any participant would individually choose [Bem et al 1965]. Each of these organizational factors acts principally to reduce the quality of the selected design.

VDT calculates several measures that are relevant to risks to the product design. Overloaded or unqualified VDT agents tend to ignore exceptions and information exchange requests, which contributes to three product risk metrics. *Project risk* measures the rate of rework or design iteration that is ordered in response to interdependencies among functionally related tasks. High VDT simulated project risk indicates a propensity for failures to coordinate inter-task interfaces. *Functional risk* measures the rate of rework (or unscheduled design iteration) sent back to individual tasks. We can interpret high functional risk for a particular VDT station agent as indicating elevated likelihood that function's or station's design module contains errors. Finally, *communications risk* is the fraction of information exchange requests that stations take time to complete. High communications risk indicates that interrelated tasks are not always sharing information appropriately, which tends to reduce the quality of design integration. We can predict overall design quality using VDT by inspecting these metrics at an aggregate project level, or drill down to evaluate the product in detail. For example, elevated project risk at the Power station indicates risk that other subsystems have not been redesigned according to their needs, and a high communications risk at the Cost station suggests risk that the estimates do not include relevant design details.

ORGANIZATION RISK

By *organization risk*, we refer to the likelihood and consequences of events that degrade the operating effectiveness of the design team (Team-X) itself. VDT measures several important pressures on the organization that can, especially over time, reduce its operating effectiveness. VDT predicts the amount of work that backlogs for each agent, and backlog can cause the sense of time pressure that researchers have shown to cause errors [Janis 1982.1]. Compounding the pressure induced by backlog is the amount of frustrating circumstance that VDT predicts including the fraction of information exchange requests that are not attended to, a fraction of exceptions that are ignored, and an amount of time that a participant spends waiting for management decisions. People who are under time pressure or stress are more likely to make poor decisions [Janis 1982.1], and errors of oversight. In addition, they are more likely to burn out and leave a position. Turnover is another risk factor for critical positions on complex projects.

In addition to understanding the baseline performance at Team-X, it is important to know whether the ICE project design has *structural stability*, or whether it is sensitive to small deviations that can be difficult to anticipate. For example, Team-X might require that a specific station be staffed by an engineer of extraordinary skill, and might stumble when happenstance requires a more average member to substitute. ICE can serve reliably in a routine strategic function only if it is effective both in optimal conditions and under foreseeable organizational and other variations.

I ran an intellective (i.e., an idealized, theorem-proving) VDT experiment that excludes many team-specific factors and found it to perform similarly to the detailed Team-X project design. The output from this experiment appears in Figure 5. In the baseline case, for example, the participants' work volumes and experience levels vary by station (in accordance with Team-X interviews), while those for the idealized case are uniform. Although I have not conducted a complete sensitivity analysis, our more generic experiment shows sufficiently similar outcomes to the tailored model that I view the project design as robust within a nominal range of staffing and task variations.

PROCESS RISK

VDT considers two measures of *process risk* that anticipate the perceived efficiency of the design study project. These are the cost and schedule of the simulated design project. My VDT model uses the total work volume among all engineers and supervisors to represent the *cost* of an ICE design project. Figure 4 shows that our calibrated Team-X model produces a similar cost structure to that reported in surveys (with the exception of meetings, which VDT does not schedule contingently, according to project performance). Although VDT calculates detailed schedules including average start and finish times for each station's task and predetermined meetings, I compare alternative cases using the *total project schedule*, or time between execution of the first and last work items.

KNOWLEDGE DISTRIBUTION

Persistent dynamics of change in the distribution of technical knowledge produce an important deviation between the traditional, hierarchical information processing theories and modern, multidisciplinary collaborative engineering behavior. My intuition is that as projects become more technically complex and dynamic, agents of superior knowledge or technical skill come to handle organizational deficiencies in work procedures and alternative sets.

VDT has been calibrated with a broad range of academics' and professionals' project study experiences, and it has made some strikingly accurate predictions of project performance [Jin et al 1995]. Because our VDT model is calibrated with the theory and experience of these traditional, hierarchical projects, it offers predictions like those of an expert in "traditional" project planning. These predictions are based on the assumption that workers route exceptions only through an authoritative management hierarchy, and that information exchange only transpires between agents engaged in interdependent tasks (or through formally scheduled meetings). Our Team-X model using the current, standard version of VDT (SimVision 3.11) matches

ICE’s common, purely hierarchical exception-handling processes from station, to facilitator, to proposal manager.

As technology accelerates, it becomes increasingly difficult for managers to maintain sufficient knowledge to resolve technical problems. When supervisors lack the specialized knowledge that is required to assist subordinates in technical work, organizations route technical exceptions to domain experts who reside either horizontally across organizational lines, or even outside the company [Monge and Contractor 1999, Palazzolo et al 2002]. In our developing theoretical model, agents continue to consult managers on preferences, but agents locate and retrieve procedural expertise from a distributed network of agents with functionally differentiated skills.

Similarly, although interdependent collaborators in knowledge work continue to provide important beliefs about the work in process, as complexity increases they become less qualified to shape designers’ ever expanding alternative sets.

COMPARING TRADITIONAL AND KNOWLEDGE WORK

Information workers’ efficiency relies upon a knowledge network that is free of expertise bottlenecks, just as traditional projects’ success rests upon a hierarchical management that is free of decision-making logjams. As the rate of change of technical knowledge in a field increases, the information processing prominence of organizational managers thus diminishes while that of technically capable experts increases [Bailey 1998]. Organizations eventually adapt to redistribute this coordination load among specialist participants. Team-X, for example, has gradually adjusted station definitions, added new stations, and substantially enhanced its information technology tool suite.

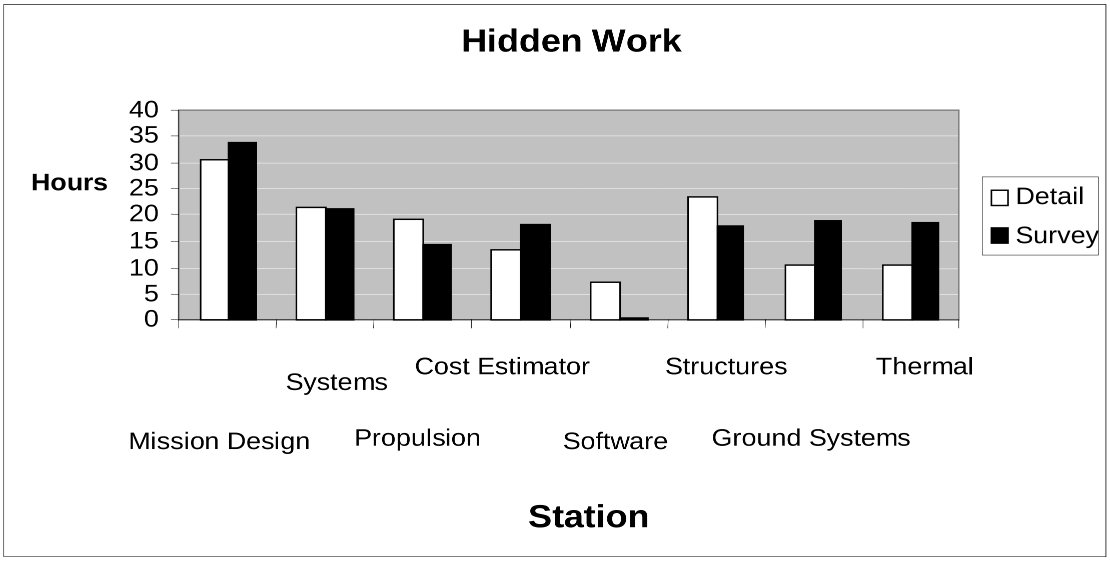

Figure 5: "Hidden work" consists of coordination and rework activities that most software systems and less sophisticated human planners fail to account for. This chart contrasts the hidden work reported in a "Survey" of Team X with the "Detail" hidden work that the VDT simulator predicts. The differences between these values preliminarily quantify the inconsistency between traditional theories and those required to account for ICE. Planners with experience limited to traditional projects are vulnerable to similar miscalculations.

I compare traditional and knowledge-network based exception handling by first reviewing the simulated (VDT) authority hierarchy results in detail. The VDT simulation does not have network-based exception-handling phenomena that are becoming increasingly common in knowledge work. Figure 5 contrasts VDT predictions against the work volumes surveyed at JPL. The JPL values incorporate the hierarchy and the technical information flow among peers that characterizes an effective ICE knowledge network.

Although management plays an important leadership role in ICE, at JPL I observed virtually no project delays that were accountable to a management bottleneck. In contrast, VDT predicts that Team-X engineers waste approximately ten percent of their time waiting for management decisions, dramatically illustrating the insufficiency of the assumed hierarchical structure. The ten percent figure suggests an amount of acceleration that projects would experience by switching from a typical, bottlenecked management hierarchy to a balanced knowledge network. Because the VDT formulation fails to capture other qualitative features of ICE practice, however, I require additional data to measure precisely the importance of discrepancies between knowledge-based and traditional work theories (or to determine whether the model can support intervention through systematic, prospective prediction). The results explained in this paper nevertheless reinforce the assertion that planners — including human ones — who depend on traditional methods (theory, experience, or models) to design a decentralized, collaborative engineering structure (like ICE) are likely to overestimate the importance of management oversight.

ICE ENABLING FACTORS

LATENCY THEORY

CRITICAL PATH ANALYSIS

Even the humblest of project models can offer actionable, counterintuitive insight into the design of accelerated projects. When confronted with complex task precedence networks, managers typically employ the critical path method (CPM) to predict and track project schedule. The CPM simply consists of arithmetically calculating the period of activity for each task, under the assumption that events will follow one another according to plan [Moder and Phillips 1983]. Tasks "On the critical (or longest) path" will extend total project schedule if delayed, and CPM suggests that these tasks receive the greatest management attention and resource allocation priority.

A project is considered "Serial" when each interdependent task is performed in turn, with only one task active at a time. In this case, the project duration equals the sum of all tasks' lengths, and accelerating any task improves overall schedule. Therefore, designers who wish to reduce serial project duration should focus on lowering the *average* length among all tasks, and may safely ignore best and worst cases (except insofar as they impact the average).

Highly compressed schedules often include many "Parallel" tasks that are active simultaneously. The ICE session is an extreme case of design parallelism, which schedules well over a dozen tasks to begin and end simultaneously. In this case, any delayed task can fall onto the critical path, and project duration equals the longest task length. Accelerating any subset of these tasks does not improve project length, and extending any one of the parallelized tasks will likely extend the project schedule. In order to accelerate a parallel project, highly parallel efforts must reduce the *worst-case* task length, and (as long as they preserve other measures like cost, quality, and risk) they may ignore average and best-case measures (except insofar as they indirectly extend the worst-case task length through interdependency). This focus on worst-case performance motivates many of ICE's most distinguishing features.

RESPONSE LATENCY ANALYSIS

When a task on the critical path requires information, its queries are also on the critical path. The amount of time that elapses between a request for information or action and receipt of a satisficing answer to that request is termed "coordination latency". Coordination latency is especially important in the most interdependent tasks because it involves a large number of information exchange and exception handling requests.

A successful executive at a technologically advanced construction company recently announced that the shortest duration his organization supports for formal information requests is three weeks. Even the best traditional engineering collaboration teams routinely require many hours or days to service internal information requests. In this environment, if each day's labor includes even one request that incurs latency, the schedules will grow significantly — while the total direct work volume registers virtually no change. Teams are liable to blame individual respondents and transactions for the project's delay retrospectively, unless they learn to pay specific attention to the systematic causes of response latency.

LATENCY OBSERVED AT JPL'S TEAM-X

Because ICE sessions condense project timelines by an order of magnitude, they amplify the significance of latency delays correspondingly. A single hour's latency, while routine and inconsequential under traditional design conditions, can eliminate over one tenth of the Team-X ICE period, waste over a dozen top engineers' time and jeopardize the project schedule. To be effective, therefore, an ICE team must minimize or eliminate all sources of delay, no matter how insignificant — indeed unnoticeable — they may traditionally have been.

I observed engineers in ICE sessions to share engineering design data in an integrated database, and issue requests verbally to readily available and qualified respondents. At Team-X, response latency ranges from seconds to a handful of minutes. Team-X's hidden work therefore does not produce the schedule expansion that occurs in conventional teams under high latency conditions. In highly parallel engineering projects, where interdependent design iteration is the norm, this one variable can easily explain acceleration by orders of magnitude.

I have used latency as a theoretical key that unlocks an understanding of the necessary and sufficient conditions for effective ICE. Reducing latency may seem conceptually simple, but it is actually multifaceted and difficult. In order to shorten latency enough to support ICE sessions, project designers must navigate many physical, social, and technological coordination barriers. In order to implement ICE, each of the thirteen fundamental enabling factors in Table 1 must consistently satisfy a corresponding success condition. Aligning each enabling factor will involve an organization-specific technique and difficulty, and attempting to accelerate without considering a given factor will tend to produce a characteristic failure mode.

Table 1: Factors that Enable Integrated Concurrent Engineering. I reason that each factor must be well managed to achieve high performance for ICE, i.e., very low (<1 minute) response latency; A shortcoming in any factor risks significant coordination latency and therefore an ineffective or slow engineering design process.

Critical Factor	Success Target	Failure Risks	Team-X Solutions
Structure Independence (Diversity, Load, Differentiation, Urgency, Interdependence)	**High:** design task work proceeds without frequent management oversight.	Delays for managerial decision-making or approval; Needless underutilization or resource bottlenecks	Culture that enables designer autonomy; frequent, rich and public review of designer choices
Task Sequencing	**Parallel** (and Reciprocally Interdependent)	Sequentially dependent design tasks are held up, waiting for others to complete work	Generic & project-specific effort to parallelize tasks; Pre- and post-sessions offload what cannot be parallelized
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Organizational Hierarchy	**Flat**: No organizational barriers or management overhead that add to latency	Decision making slows awaiting exception resolution by overburdened or multi-tier management	One facilitator, no managers; Management responsibilities distributed; Tools, collocation magnify effectiveness

Critical Factor	Success Target	Failure Risks	Team-X Solutions
Psychology and Culture	**Egalitarian yet Intense**: Team members respect each other in a high pressure environment	Infighting, over-conservatism, defensiveness; Fatigue	Participant training and selection; Functional organizations authorize design elements
Goal Congruence	**High**: Participants aspire only to project success.	Debates on process, decision flip-flops, inappropriate rework	Culture; facilitator attention; Persistent wall projection of formal goals
Process Equivocality	**Low**: Procedures and goals are well understood and accepted	Extended debates about process or priorities	Culture; Experienced facilitator leads process
Interpersonal Communication Topology	**Pooling**: Members resolve problems very quickly in groups of two or more	Inability to explain a design choice appropriately causes confusion and delay; personal style detracts from group performance	Collocation; Persistent wall projection of design predictions; Voice loops in distributed implementations
Integrated Conceptual Models	**Semantically rich**: modeling applications of multiple disciplines share their common data, but not their discipline-specific data	Indefinable and coarse, or excessive levels of detail cause confusion or excessive management effort	Careful design of the project ontology implemented in the (Excel-based) ICEMaker database
Design staff focus	**Committed:** Design session participants focus exclusively on project work during design sessions;	Delays waiting for workers who must also attend to needs of other projects	All participants dedicated to the task during design sessions; short design sessions to allow availability of highly skilled designers

Critical Factor	Success Target	Failure Risks	Team-X Solutions
Communications Media/ Technology Richness and Fidelity	**Rich:** Shared and personal, visual, multi-disciplinary, showing functional requirements, design choices and predicted behaviors	Inability to provide detailed and accurate design description to all stakeholders quickly and easily; Confusion, misunderstandings, and duplication of effort	Personal workstations; shared displays of an iRoom
Discipline-Specific Modeling and Visualization Tools	**Strategic:** Balanced so that all potentially critical-path tasks are accelerated	Manual design tasks bottleneck project schedule	Decision support tools accelerate critical path tasks
Information Network	**Closed:** All tasks' requisite knowledge, procedures, options, and authority are immediately available.	Delay for access to design interpretation or decision-making	Heavy reliance on collaborative design sessions; designer collocation during design sessions; careful selection of chairs and participants for each design session

A common intuition is that measuring and incrementally adjusting the enabling factors toward success conditions can substantially improve many projects' schedules, even without committing to full-blown ICE. However, it is possible that ICE is rare because it requires maintaining a fine balance among enabling factors. This systems perspective indicates that because many of these factors are interdependent, isolated changes might produce few benefits, or prove detrimental. Future research will involve designing a suite of simulations to explore which changes may be safely performed in isolation, and which must be performed in concert. For now, I suggest that organizational designers who seek to improve their collaboration effectiveness through latency reduction should attempt to co-align *all* of these factors within their specific organization; Aligning only a subset of these factors will reduce project duration far less.

Table 1 and our subsequent explanations offer fundamental explanatory power that may facilitate the evaluation of new ways (such as teleconferencing) to support ICE. Prior analyses of collaboration often focus on higher-level factors than those I list. For example, collocation provides a pooled communications topology and allows a closed information network, while enhancing focus, communications richness, and an intense yet egalitarian culture. The JPL Team-X shared database technology reduces process equivocality and enhances communications richness and fidelity. "Structure Independence" is a particularly subtle compound factor for which I offer specific guidance.

SOURCES OF LATENCY

TASK SEQUENCING

Figure 3 illustrates a range of approaches to task sequencing. In the serial approach, each design task completes before the next begins, generally requiring the least coordination, costs, and risk, but taking the longest to complete. When project duration is more important, project designers begin to "Fast-track" or overlap tasks with the fewest dependencies. For example, in building construction framing is followed by electrical work, and then sheetrock. A fast-tracked building project might start rough electrical and plumbing work once a large enough area of walls has been framed, and sheetrock the walls immediately behind the electrical and plumbing teams. Design projects often attempt to execute tasks entirely in parallel, executing them all at the same time. Because each task is dependent on information that collaborators are constantly changing, this strategy is difficult to coordinate. In some cases, the interdependency between tasks is so strong and one of the tasks is so clearly the “driver” with priority in making its decisions, it is not possible to parallelize tasks.

ORGANIZATIONAL HIERARCHY

A project’s authority system ensures that participants know the tasks they must execute and the organization’s goals for their performance. The traditional authority system, based on a multilevel management hierarchy’s information processing capacity, is not designed for the pace of ICE session demands. This section explains how the need for management direction interacts with the processes of ICE.

For more than a century, the hierarchical structure of authority has played a central role in management theory [Fayol 1949]. Because ICE depends less on this mechanism, as evidenced by its structure of 15 subordinates to one manager, understanding the new organizational form requires us to explore more modern theories.

In 1967, Thompson defined reciprocal interdependence between two tasks as “the situation in which the outputs of each become inputs for the others” [p.55]. Thomsen et al 1998 defined reciprocal interdependency between two tasks more rigorously. He proposed that it arises due to negatively interacting, shared sub-goals of two tasks — i.e., a choice that is better for one or more sub-goals of one task is worse for the other in terms of those sub-goals. This definition fits a range of projects, including many engineering efforts that have been recently parallelized in response to increased pressure. Thompson further proposed “Under norms of rationality, organizations group positions to minimize coordination costs" [p.57] and "Organizations seek to place reciprocally interdependent positions tangent to one another, in a common group which is (a) local and (b) conditionally autonomous" [p. 58]. Workers engaged in interdependent tasks coordinate heavily, and mutually adjust until they find acceptable solutions. Thompson recommends assigning these projects to teams that are in close organizational proximity. According to this theory, interdependent engineering projects can benefit from a flat hierarchy's reduction in coordination costs and delays.

I believe the uncommonly flat structure of effective ICE is essential because the alternatives' information processing delays would decimate performance. Some of the earliest literature on organizations shows that assigning more than one manager to oversee the same task can create many problems, including delays through the divergence of priorities and processes **[**Fayol 1949**]**. Research on the matrix structure indicates that it would typically create similar delays (although in other applications, this organization creates offsetting benefits). Thompson [1967] and Galbraith [1977] indicate that trying to avoid these problems with a multi-layer hierarchy imposes routing delays. For example, introducing middle managers for science and engineering at Team-X would unacceptably delay the rapid flow of interdependent information processing between these two disciplines. Thus, by a process of elimination, as well as by direct theoretical reasoning, I conclude that ICE *requires* an extraordinarily flat management hierarchy.

Because managers have insufficient bandwidth to closely supervise this many engineers simultaneously, the feasibility of ICE for a given project relies on members' independence. The ICE project is able to advance beyond the theoretical limit of seven (plus or minus two) subordinates [Miller 1956] because ICE distributes the traditional responsibilities not only to the facilitator, but to others as well. I have already explained how changes in the distribution of technical skill release ICE facilitators from serving as technical authorities. Instead of coordinating through management, a proposal manager represents the customer directly to the team, and ensures the consistency of project goals. Facilitators are safely distanced from the functional stations' personnel reviews because, in an open setting, technical skill is a psychologically natural method by which peer groups police themselves [Festinger 1954]. Managers need not conduct the typical status report meetings, because the ICE facility provides an automated, persistent display of team members' aggregated progress. Finally, participants are authorized to make intermediate-level decisions according to their own judgment, rather than consulting with a middle manager.

STRUCTURE INDEPENDENCE (AN IVA MODEL OF ICE)

Interaction Value Analysis (IVA) models project conditions that support the "lightweight" management and informal communication that ICE requires [Nasrallah et al 2003, Nasrallah 2004]. Using mathematical queuing theory and a game theory analysis, IVA demonstrates that imposing structured communication channels on agents improves organizational efficiency only under a limited set of circumstances, compared to allowing agents to select with whom they prefer to communicate. Because IVA's predictions are for long-term performance, setting realistic expectations and budgeting for ICE's learning curve may be required to develop an effective ICE team.

According to this analysis, an ICE application should satisfy one or more of the criteria that Nasrallah et al identify, and that I reproduce in Table 2. If the project satisfies (or is altered to satisfy) just one of the criteria, it is likely, in time, to naturally develop perfectly efficient operations (in which Pareto optimality equals global optimality). The latency theory indicates that ICE can support structurally independent projects, if other factors are also in line.

In contrast, other projects that do not achieve at least one of the IVA criteria are unlikely ever to develop efficient (globally optimal) operations without sustained management intervention, because substantial inefficiencies in resource allocation will result from the removal of a management-imposed, globally optimal communication structure. Our analysis suggests that under these latter conditions, the project is not amenable to ICE because the procedural management bandwidth exemplified at Team-X will never suffice.

Table 2 (Columns 1 and 2 reproduced from Nasrallah, Levitt, and Glynn [2003]) The mathematical Interaction Value Analysis model indicates that management structure adds little long-term value to a project when *any* of the factors listed achieves the value in the second column. As an example, JPL's Team-X does not require rigid organizational structure and its diversity is high- each participant employs a unique discipline, which agrees with the prediction of IVA. I argue that ICE cannot accommodate projects that fail this test and therefore require a large amount of imposed management structure.

Alternate Factor	Target	Team-X	Factor Definition
Diversity	High	High	The number of independent skill types possessed by parties in the network
Interdependence	Low	High	The degree to which parties with distinct skills need to collaborate in order for their individual tasks to be of value to the organization
Differentiation	Low	Low	The contrast in skill levels between the most skilled and the least skilled parties for a given skill type
Urgency	Low	High	The rate at which pending work becomes useless if not completed
Load	Medium-Low	Medium-High	The demand for work relative to resources

GOAL CONGRUENCE

In ICE, egalitarian culture and respectful individual personalities must govern conversational initiative based on technical concerns, instead of rank and forcefulness. Beyond merely possessing competence, ICE requires that all participants *maintain a reputation* of impartiality and authority. Shortcomings here can lead to design conflicts, loss of team cohesion, and the need for intervention by functional managers who reside outside the ICE session.

A crisis of respect can introduce considerable latency. Because of the high interdependence among design variables, the coordination that is necessary to resolve any conflict or indeterminacy among participants' preferences could delay the entire project beyond the 2-3 hours of a single ICE session. Furthermore, an incompetent or politically motivated participant can easily create a cascading degradation of the design (even resulting in an unworkable result). Finally, when this kind of incompatibility is diagnosed, it might be necessary to replace a team member. Among other costs, this would engage the politics and corresponding latency of the stations' traditional human resource organizations**.** Even under the best conditions, any one of these events could delay a design session by hours or more- a disaster under the accelerated ICE timeline.

Even if goal conflicts do not actually manifest, organizations must typically act to mitigate the perceived risk, thus compromising baseline performance [Coase 1937, Williamson 1975, Milgrom and Roberts 1992]. For example, an ICE organization must carefully police itself for crises of professional esteem and conflicts of interest. In a public conversation, I saw a Team-X facilitator discover that one engineer was using much larger design safety factors than his peers. This disproportionately protected the engineer's subsystems from outside scrutiny. The facilitator took time out with the engineer in a private discussion, presumably to address the potential perception of self-interest and head off a public crisis of confidence. In another case, publicly resolving a more broadly recognized dispute helped restore the community's confidence in all concerned.

The requirement for congruent goals can limit ICE's direct applicability. For example, individual branches of government might effectively operationalize administrative directives using ICE. However, it is not clear how a group of government elected representatives could use ICE to craft legislation because their constituents have differing priorities. Two structures that lack goal congruence but match many other ICE characteristics are Team-I at JPL and ReVeL at Stanford. Our brief observations of those teams indicate that goal clarification exceptions emerge frequently, but they are handled with extraordinary effectiveness (even under equivocal conditions).

PSYCHOLOGY AND TEAM SPIRIT

One of the most commonly mentioned criteria for Team-X participant selection is that for many, the work environment's chaos is intolerably stressful. Participants are exposed to multiple streams of conversation, and must filter them for key words of interest — without losing productivity on individual tasks. This level of activity provides some error checking [Mark 2002], but it also psychologically drains participants and motivates Team-X to limit design session durations. The ICE experience of excitement and community in many ways resembles deindividuation [Festinger et al 1952], and its effect on design information processing is not known. Theories presented by Zajonc [1965] suggest that the pressure of group scrutiny improves ICE designers' performance but limits their ability to learn on the job. Recent studies by Monique Lambert on transactive memory at Team-X support the latter prediction [Lambert and Shaw 2002, Lambert 2005].

The flat hierarchy also has a psychological impact on individual performance. Even distinctions between members as inconsequential as eye color, when brought to team members' attention, can divide otherwise egalitarian communities [Kral 2000]. A "superordinate" or unifying goal of greater perceived importance can nullify this type of unwarranted antagonism however [Sherif 1961]. Research has shown that the best team performance occurs when workers are not only motivated but also share personal goals. According to these theories, compared with separation into different departments, focusing the ICE team's attention on shared goals will improve group cohesion and therefore enhance performance. ICE sessions lack a common unifying force between managers and engineers, because the former are absent. Direct personal communications among team members builds coherence, and the facilitator and proposal manager reinforce the superordinate goal of design effectiveness by persistently projecting and referencing integrated design performance metrics. This improved coherence and morale is especially important to ICE because each position's consolidation of technical skills provides more organizational power [Kotter 1977] and opportunities to "Spin" (an abuse of uncertainly absorption [Simon 1977]) or "Hold-up" the team to exact personal benefit [Klein 1991].

ICE depends upon an egalitarian and respectful culture, and participants' competence and *reputation,* to dissolve dependency cycles in "sidebar" negotiations rapidly. This requirement is akin to Weick and Roberts' [1993] concept of "Heedfulness" as feedback and mutual adjustment in a "Collective mind" [Erickson 2004].

This research does not focus on the quality of ICE teams' output, other than to note that Team-X is perceived to have been highly successful within its market context. It is noteworthy, however, that ICE teams must be wary of groupthink [Janis 1982], which can accelerate a process but reduce quality by limiting the thorough and critical evaluation of selected alternatives. They must also sustain awareness of the "Risky shift" phenomenon [Bem et al 1965] that can produce riskier team choices than individuals would independently select. However, these hazards of collective decision-making are somewhat offset, theoretically, by the combination of group communications and egalitarianism. Just as Weick's aircraft carrier workers each may prevent, but may not individually permit a landing [Weick and Sutcliffe 2001], or Just In Time Manufacturing stations may "raise the baton", each chair at Team-X may announce to the group that their station requires broad design configuration changes.

PROCEDURAL EQUIVOCALITY

A work task is called *uncertain* when it requires data collection, or when an (a priori) unidentified set of variables impacts it. When there is no clear procedure to execute a task, or to evaluate its outcome, that task is called *equivocal* [Burton and Obel 2004]. For example, selecting a child's gift can be equivocal, while predicting the color of the tenth car to arrive at an intersection is merely uncertain. Table 3 compares the posited impacts of goal congruence and procedural equivocality on ICE.

Table 3: Industries and projects have varying certainty in goals and procedures. ICE's limited management bandwidth requires clear goals and procedures.

	Clear Goals	**Equivocal Goals**
Clear Procedures	ICE functions well	In ICE, product debates stall progress
Ambiguous Procedures	In ICE, process debates stall progress	In ICE, monotonic progress is not guaranteed

Although uncertain tasks require increased coordination, workers with sufficient time and information resources can systematically complete them. Under equivocal conditions, however, debate over the method or form of solution may protract a study indefinitely. To prevent this greater controversy and duration variance from jeopardizing project performance in an ICE setting, JPL's functional organizations limit the equivocal "rocket science" of subsystem design and analysis to a merely uncertain "paint by numbers" subset in spreadsheet form. This aspect of the latency theory predicts that new ICE applications can only perform adequately if they resolve in advance any indeterminacy in methods and solutions' required levels of granularity, fidelity, and scope. Doing so may require prior enumeration and certification of technical parameters, or establishment of a timely and reliable conflict resolution process.

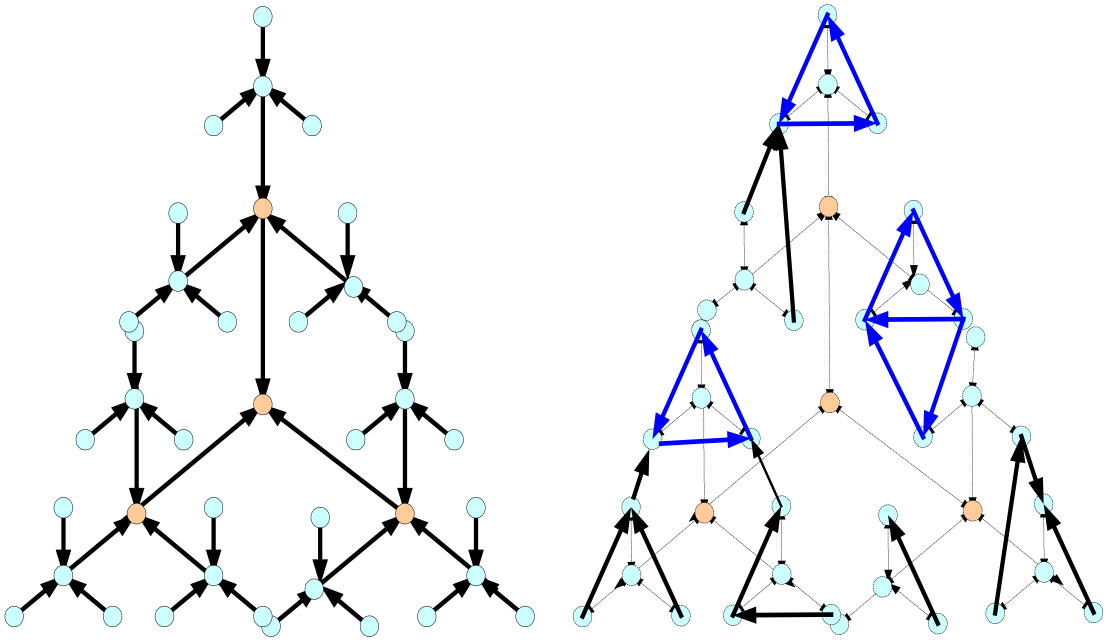

Figure 6: Typical arrangement of engineers (circles) and communication links (arcs) in traditional (left) versus ICE (right) organizations. The graph at left shows a typical hierarchy of traditional information demand — a flow that is opposite to the flow of decisions. Displaying the traditional 'org chart' in this format, with senior managers encircled by their subordinates, facilitates the cognitive leap from tree to network information flow (at right). At right is a typical information flow mandated by the task interdependence and the expertise of organizational agents. Ordinary interdependence produces cycles that motivate organizational adaptations such as group communications, integrated concurrent engineering, and elimination of managerial bottlenecks.

SPANNING INFORMATION NETWORKS

When a traditional engineering project requires knowledge that lies outside participants' domains of expertise, it may comfortably leverage outside technical resources. An ICE team does not have this option because it incurs a traditional organization's large response latency. Even though Team-X keeps an expediter on hand to ensure rapid follow-up when outside experts are consulted, because of projects' high task interdependence, the action still jeopardizes a design session's schedule.

Team-X team uses virtually complete and continually available knowledge networks for each technical discipline. It requires a collection of engineers who possess technical expertise to address all of a space mission's principal design elements. The requirement motivates each Team-X station to ensure the continual completeness and accessibility of requisite information (facts, procedures, choices, and priorities).

COMMUNICATION TOPOLOGY

Traditional projects' information distribution systems (such as the knowledge network and authority hierarchy) are both intentionally designed and naturally evolved to optimize average performance. In contrast, ICE must design these to minimize worst-case performance, because there is no slack time to absorb delays.

In mathematics, the common lay term "hierarchy" refers to a directed, acyclic graph structure or "dag". Interpreted organizationally, each "node" represents an agent (and his or her tools) that processes information, and arcs represent dependencies. Under this simple mathematical model of decision-making and information exchange, a hierarchy effectively and efficiently (in logarithmic time) distributes information and gains closure. I diagram this model in Figure 6.

A worst-case scenario emerges, however, when many dependencies stretch across the decision dependency network, and cycles among these two-person "arc" relations occur. For example, consider that a spacecraft's power systems engineer relies on propulsion to define requirements, while propulsion in turn is based on trajectory, and trajectory requires input from the power systems engineer. Unless the same knowledgeable and attentive manager supervises them all, the team may not recognize the endless sequence of ensuing requests in the dependency cycle. This problem typically occurs when two fast-tracked tasks are delayed enough to overlap unexpectedly with a third. Similar cycles and unreasonably long paths through the dependency network magnify latency to produce endless delays in collaborative engineering, phone trees, and bureaucracies [Eppinger 1991].

ICE teams diagnose cyclical interdependencies by observing multilateral interdependence in a shared workspace and formulating a mutually agreeable solution. The "massively parallel" Team-X resolves interdependencies quickly in ICE "sidebars" and a shared database that enables all members of a decision-making cycle to virtually pool facts, preferences and alternatives (sometimes under the procedural guidance of a facilitator). Mathematically, I view this process as encapsulating a subset of the graph that contains cycles into a "sidebar node".

The preceding analysis indicates that ICE facilities must support multiple, simultaneously communicating groups. Team-X implements this solution through physical collocation, in which interdependence is passively communicated through physical location and solved through impromptu, face-to-face sidebar conversations. Because there are multiple knowledge networks in effect (one for each domain of engineering), I conjecture that ICE requires support for the activation of multiple cycles in communication support. This explains the fact that in spite of contrary hopes and expectations [Su and Park 2003], JPL has found that even the highest end videoconferencing technologies currently do not yet adequately substitute for the collocation of core engineers under ICE. A zero-latency, life-size HDTV communication channel between two collaborating teams of engineers provides a one-to-many broadcast mechanism that crosses location boundaries, but does not enable multiple, simultaneous, impromptu group communications [Mark and DeFlorio 2001].

In contrast with the cited experiment by Mark and DeFlorio, simultaneous interlocking private communications channels, commonly known as “voice loops” in space mission operations [Patterson et al 1999], might enable distributed ICE teams. Individually, voice loops are like conference calls, some of which integrate the same station in each project, and some of which are created on the fly as needed. Users log into and out of the loops dynamically, and (like Team-X) monitor all of the conversations that might impact their work. In addition to defining the key loops for an ICE application, developers must either support user mobility (presumably through headsets) or sacrifice a key indicator of project status [Mark 2002].

FOCUSED PARTICIPANTS

Like most information workers, engineers are often committed simultaneously to more than one project, and often possess peripheral responsibilities like recruiting and organizational governance. Under ordinary circumstances, these projects might compete with an engineering project for a worker’s attention. An ICE project cannot afford this kind of lapse, however, because it may interfere with the team’s coordination requests. Participants are therefore required to attend exclusively to the ICE project throughout design sessions.

Many organizations are reluctant to release the highly qualified individuals who can perform in ICE projects unconditionally to dedicate their efforts to a single project. Unless a team member can temporarily delegate or suspend his or her outside responsibilities, conflicts will undoubtedly arise. Minimizing the disruption of external projects motivates Team-X to limit design sessions to three hours and to distributing them through the week.

RICH MEDIA

When considering new ICE applications, it is important to consider the pressures of rapid communication and the ability of available analysis and visualization tools to support the work. Insufficient communications media and protocols can magnify differences between the subjective worldviews of distributed groups of collaborating space mission designers, causing a range of linguistic and procedural shortcomings [Mark et al 2003]. When coordinating during intense design sessions, engineers may feel that meeting the project requirements requires rapid communication. However, accelerating information flow beyond the fidelity of available media can undermine accurate delivery of the messages. Imprecise or incomplete correspondence may spawn misunderstandings that require clarification or even rework.

Team-X communicates many design variables among participants formally, through a shared database. Their mature integration method allows the advance specification of data structure and validation, and transfers information at virtually no cost in lost precision, time, or effort during the design session. Gestures and facial expressions offer improved fidelity to collocated groups. I have observed more complex, but similarly rapid and precise media at Team-X including screen-projected spreadsheets, 3D craft structure and trajectory visualizations, and hand-drawn art. The observed diversity of rich and precise media at Team-X supports the latency theory.

CONCLUSION

I offer coordination latency as a unifying, intuitive, descriptive performance metric, and I propose the goal of reducing it to near-zero as a project design principle. This latency theory indicates that all collaborative arrangements operate at a readily quantifiable level of efficiency and reliability. I suggest that every organization can benefit from an audit of individual latency sources, and, perhaps, continual (if statistical) tracking. When compared with traditional organizations, I find that ICE appropriately pays careful attention to average and worst-case coordination and exception handling latency, without undue concern for practices targeting best cases. Improving the likelihood that engineers have the information or decisions that they need as soon as they need it allows the stations to move forward at a greatly accelerated, synchronized pace. ICE can be viewed as the “Just in Time” approach to knowledge work, in that it supplies four simultaneous information flows with infinitesimal latency (“lead time”) and high micro-scale reliability (“service level”).

DISCUSSION

REMARKS ON METHODOLOGY

In recent years, the computational modeling of organizations has enjoyed a popular resurgence among researchers seeking to better understand new and established theories [March 2001 and Burton 2001]. By grounding the micro-behaviors of an agent-based computational model explicitly in a theoretical framework, researchers can explore complex ramifications of a micro-theory (or set of theories) that extend qualitatively beyond the reach of human intuition. In addition, our team has used models to quantitatively predict the effects of theoretical and practical changes in a baseline model. In this paper, I apply the technique as an engineering method that relies in part on intuition and external observation to validate its claims. Therefore, I accompany our model analysis with intuitive descriptions and observational data.

The recent expansions of particularly compatible social science theories and analytic techniques are creating an exciting time for computational organizational modelers [March 2001 and Burton 2001]. Properly applied, the methodology facilitates practical organizational design just as effectively as it strengthens scholarly results [Kunz et al 1998]. Our work illustrates the power of computational organizational models to both extend, and lend specificity to, qualitative theory, ethnography, and survey research.

In planning a project or adapting one midstream, managerial interventions are sometimes directly imposed on the organization or work process. At other times, it may be more economical to test these interventions first in a computational model.

Schedule tracking systems such as Primavera are the most frequently consulted quantitative project models, but they are not the most sophisticated. When testing interventions in the Virtual Design Team (VDT) simulator, for example, planners can compare project participants' predicted backlog, coordination effectiveness, schedule risk, and other results between many alternative work process and organizational configurations [Kunz et al 1998; Jin et al 1995, Levitt et al 1999]. In this way, modelers can plan joint adaptations to organizations, processes, and culture that will meet a project's goals. In time, our team believes tools like VDT will enable us to engineer projects with a comparable methodological rigor and confidence as is demonstrated in the engineering of today's buildings or automobiles. In VDT, for example, we can select from a list of alternative intervention scenarios, and simultaneously compare the results of multiple cases. By weighing predicted agent backlog, project cost and schedule, and task quality outcomes between alternative cases, VDT users can jointly design and adapt organizations, processes, and culture in order to meet a project's goals.

Every model contains assumptions that limit the range of its results' applicability. Many of VDT's basic assumptions are fairly well documented and understood. As a result, modelers have been able to apply the system successfully in a very broad range of settings. For example, the authors have personally developed VDT models of projects as diverse as aerospace engineering, facility design and construction, and software development.

The modeling project at Team-X was noteworthy for bringing to the fore particularly many circumstances within which VDT had not been tested. Limits of the VDT model include:

- No explicit product model
- FTE allocations fixed over project life
- Meetings never scheduled on-the-fly
- Exceptions, communications are only 2-way
- Exceptions use reporting hierarchy, not knowledge network
- Work difficulty modeled as routine
- One task, skill, agent per station
- An unanticipated project scope extension was not included
- Limited distinction between rework and design iteration

Ongoing research to develop POW-ER, a successor to VDT, is addressing many of these shortcomings.

REMARKS ON ICE

Although I retrospectively calibrated VDT to show the same project coordination volumes reported by Team-X participants, the simulated distribution of hidden work among individual tasks did not match perfectly (Figure 4). This may result from the traditional, hierarchical framework's inability to predict bottlenecks in the participants' knowledge network. Based on this result, I alert organizational designers who are steeped in traditional theory to the danger of underestimating the coordination load that technical experts will experience in decentralized knowledge-based projects such as ICE.

Many aspects of JPL ICE sessions' product, organization, process, and environment are distinctive, modern, dynamic, and resistant to conventional intuition.

I have found that mainstream organizational theories, computational models based upon them, and prior work on accelerated projects each shed light on the new form. However, the literature does not fully explain why the extremes of parallelism, interdependence, and decentralization permit the radical schedule performance gains that Team-X claims. I have integrated and extended extant organizational theories in an intuitive manner to enable a more detailed and broadly applicable analysis that provides initial insights to begin answering this research question.

I have drawn attention to and shed light upon two principles of knowledge work. The first is that modern organizations supply four distinctive elements of a general rational framework: beliefs, alternatives, preferences, and procedures (or decision rules) [March 1994]. Knowledge-based exception handling particularly highlights the increasing dependence on, and interdependency among, the technical labor force's domain experts. Organizational designers cannot afford to continue discounting these phenomena or addressing them with short-term solutions. Instead, organizational diagnostics may trace characteristic dysfunctions to precise failures in meeting each of these needs. Today's knowledge and expertise holdups may resemble yesterday's management bottlenecks, but they also herald an entirely new set of organizational dynamics and corresponding opportunities.

What enables a group of interdependent engineers the size of Team-X handle their coordination loads, while keeping exception handling at a level that a single facilitator can manage? I believe the answer is a coordinated program that reduces the latency of information flows.

These flows are the processing and distribution of preferences, procedures, alternatives, and beliefs appropriate to concurrent design decision making. A process of advance selection, clear definition, and facilitated emphasis and monitoring of project targets supplies the ICE engineers with a consistent set of priorities. Procedurally, a facilitator guides the team using an informal and flexible mental map of processes, so that every engineer's next step is always clear. At the same time, each engineer possesses a clear set of alternative design choices that will be acceptable to his or her organization, and engineers negotiate agreements in groups to scrutinize compatible, complementary sets of alternatives. Decision support tools help the engineers calculate the ramifications of these choices in minutes, while a shared database propagates information efficiently though the organization.

Although features such as collocation and shared databases are prominent among discussion of high performance teams, our reasoning suggests that these elements serve fundamental theoretical purposes. As a guide, I assert that a principal consideration for all of these alternatives should be the reduction of latency. I argue that, in any project, each of the major information flows can be effectively measured and improved by careful attention to the response latency metric and the factors that contribute to its escalation. Organizationally, this may range from collocation to simply discussing patterns of delay among divisions. Technically, projects might monitor the average delay of workers in listening to voice mail.

From a theoretical standpoint, I have also shown why Team-X's broad hierarchy, massive parallelism, and low latency are able to produce radical schedule compression. The distinctive Team-X products, organization, processes, and environment each serve a broad range of enabling factors that I believe all highly accelerated projects must accommodate.

Even in domains where ICE is viable, many organizations may fail to navigate its many challenges and pitfalls. In our view, however, radical project acceleration through mechanisms like ICE presents both practitioners and theorists with an opportunity they cannot ignore.

Evolutionary organizational theorists [Hannan and Freeman 1989] would likely predict that if ICE performance were viable, the approach would be more widespread. The system perspective I present in the introduction suggests that this apparent conflict may result from a careful balance of factors that are not ordinarily available in combination. For example, moving to a flat hierarchy or task parallelism, alone, might be disastrous in a traditional organization, even though they are complementary in ICE.

In future research, I plan to design a computational experiment to investigate this issue by calculating the predicted impacts of combinations of enabling factors. I believe this analysis can illuminate the interactions between enabling factors and lead to improvements in both ordinary engineering and less traditional methods.

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