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Observation, Theory, and Simulation of Integrated Concurrent Engineering: Risk Analysis Using Formal Models of Radical Project Acceleration

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INTRODUCTION

Design Team Performance

Integrated Concurrent Engineering (ICE) uses: a singularly rapid combination of expert designers; advanced modeling, visualization and analysis tools; 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, MEP, Olsens] 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 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

We find that an auto metaphor conveys our intuition that in spite of superficial differences, ICE mechanistically differs from standard design principally in that it operates more rapidly. Metaphorically, we 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 racecar 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

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

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 principally responds by reflex in accordance with training and experience, because there is little time for deliberation. An ICE team also must 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), we are still looking at a car (or a multi-disciplinary design project), and we can understand it by understanding the behavior of the fundamental mechanisms.

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 racecar 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, and offer a key to understanding phenomena as seemingly unprecedented 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 are likely essential to that endeavor. *This paper addresses the theorists' questions of how and why ICE works.* Most early descriptions of ICE are anecdotal, motivational, or limited in perspective, rather than being grounded rigorously in broadly validated theory. Recent scholarly documentation published on the behavior of ICE and similar projects [Mark 2002, Teasley et al 2000] describes the features of ICE, namely highly concurrent design by multiple collocated multi-disciplinary experts. The academic literature also 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 this move prohibitively challenging in the short term. We identify for practical organizational designers a process performance metric that can help teams understand the limits on their performance today and a focus of attention that can significantly improve their effectiveness in any kind of collaboration.

Our Methodology

We offer three orthogonal and complementary research elements: *observations* of a radically accelerated project at JPL, formal yet intuitive *theories* that have face validity and offer a straightforward comparison with established social science theories, and *simulation results* that show the combined implications of foundational micro-theories on a project scale. 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 formalism.

Observation

We visited JPL's Team-X and ethnographically observed three design sessions of a sample project. In several hours of on-site interviews, we collected quantitative and qualitative details about the participating organization, process, and culture. Finally, after coding and analyzing this information, we followed up with an online survey covering the amount of time each participant spent in direct work, communication, and rework each week. We 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. We 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 we leverage existing literature extensively, the work also draws on behaviors and relationships observed in practice.

Simulation

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

VALIDATION OF ICE ENABLING FACTORS

Inspired by ICE's novelty and differences from traditional structures, we explicitly assess the practice's amenability to previously established organizational theories. Although it does not tell the whole story, much of mainstream theoretical research on organizations does apply to ICE. Theoretical developments led by vonNeumann and Morgenstern, Simon and March, Thompson, and Galbraith [all more precisely] offer points of departure for our exploration of parallel engineering teams' work and structure. At the project level, we find that traditional organization theories are applicable and insightful, while at a more detailed level, we find that important questions remain. In this section, we synthesize established organizational theories into a foundational framework that accommodates both ICE and traditional practice. We instigate and terminate this process by comparing observed ICE behavior against the predictions of theory-grounded computational models.

An OrgCon Model of ICE

We began our analysis using a computer program that is firmly rooted in a range of established organization 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 informed of characteristics 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.

We applied OrgCon to a hypothetical company that conducts the majority of its business as we 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

We 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 (we explore the importance of this and other features, such as "Ambiguity", "Richness of the media", and "Team spirit" later in this paper). The result lends confidence in the OrgCon model's applicability, and demonstrates that elements of ICE's success can be predicted by existing literature.

By predicting no misfits for the ICE approach, OrgCon raises the exciting possibility that ICE is a new, distinct and effective organizational form. Many organizational researchers (notably Mintzberg [], and Burton and Obel themselves**)** hypothesize that only a handful- typically 5 or 6- perfectly adapted archetypal organizational styles exist. 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, we cannot conclusively determine whether an important gap in theory, observed practice, or model is present. We 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) indicates that organizations operate as if their primary function is the processing of information. Shortcomings in information flow or knowledge in an organization produce "exception" events that require managerial attention. We interpret exceptions as perceived faults or gaps in the decision basis that disallow "Clarity of action" [Howard]. Organizations route the information or queries that are pertinent to these exceptions to complementary resources such as management. 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, micro-level information processing view of exception handling motivates the formation of Team-X, while the latter, nano-level demands of individual communications drive the group's structure and information technology configuration.

Direct Work

We 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 appropriateness [March 1994, Scott ibid., Powell and DeMaggio]. 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 [vonNeumann and Morgenstern year, March 1994], individuals make decisions by combining four elements: beliefs, preferences, alternatives, and a decision rule. Alternatives are possible actions (including passiveness) amongst 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, Howard and Raifa]. 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 may approach rationality.2

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. We 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. 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. 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 feature-rich model of hidden work. For a detailed description of VDT mechanics, see [Jin and Levitt CMOT]. We 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.

We offer a micro-level view of information processing on the four elements of the decision basis. Engineering actors 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, actors occasionally encounter decisions for which elements of the decision basis are inadequate, unavailable, or incorrect.

Exception Handling

Organizational actors 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 reworked. In the model, they emerge probabilistically during work, with a frequency based on task

[2] Prospect theory [Kahneman and Tversky] 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.

complexity measures, as well as on the adequacy of the assigned actor's experience and skills. 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 and functional). Because management is the clear authority on organizational preferences, and also –in traditional organizations- the repository of superior technical knowledge, the hierarchical VDT exception-handling model captures a micro-organizational adaptation to uncertainty in the decision bases' preference and decision rule components.

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 actors, 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 properly review the exceptions, 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. These facts 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 actors request information from others who are engaged in interdependent work (at a rate that is based on actor skill, prior team experience, and task uncertainty). In this situation, the simulator routes a virtual information request and possible reply between the actors. Because this process supplies actors with data produced in other activities, and this data influences the range and significance of design options, we view the VDT communications model as capturing a micro-organizational adaptation to gaps in the belief and alternatives components of the general rational framework's decision basis.

When an actor performs a task that has a very large number of interdependencies, the time spent in communications may actually exceed the amount of direct work activity. If the workload becomes unmanageable, quality may degrade significantly- not just for the principal task, but also for others who rely upon the activity's output.

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 volume and distribution of rework. Rework results from handling exceptions conservatively, and consists of performing an activity (or subtask) a second (or third) 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 a 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 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 design iteration, instead using the same exception handling simulation for both cases.

Simulating Team-X Using VDT

To build a VDT project model of Team-X, we created 15 virtual engineering stations, as well as a facilitator and proposal manager, and we 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 actors working, exchanging information, and handling exceptions.

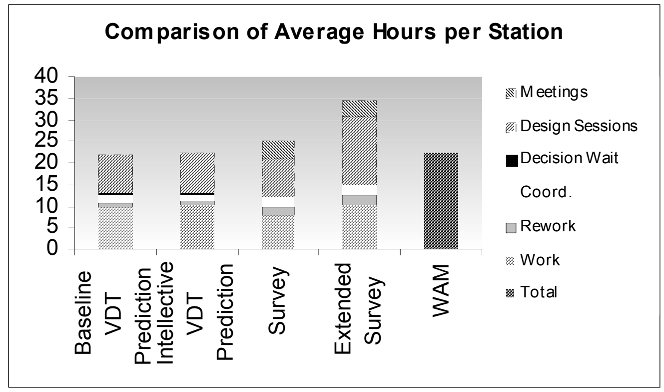

Figure 3: Comparison of work volumes on a sample JPL Team-X project from various sources. The columns represent (right to left) reported, predicted, surveyed, simplified/simulated, and retrospectively simulated data. At a high level, there is agreement among them.

Figure 3 compares an average number of work hours per station, by type of work activity and according to a number of sources. Prior to project start, all Team-X participants requested a time budget to do their work, which we averaged as the rightmost Work Authorization Memo (WAM) value. The Survey column reports the data participants provided after project completion. We 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 3 illustrates that using input data collected at JPL (including work volumes reported retrospectively by Team-X) we were 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 distribution of work for this type of project. Because the simulation is rooted in the information processing theory, this result coarsely cross validates the information processing theory, ICE observations, and VDT computational model.

ANALYSIS OF ICE RISKS

Performance Analysis and Risk

VDT provides a range of product, 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. We describe the VDT outcomes as measures of risk to the mission design product, the Team-X organization, and the conceptual design process.

As a Monte Carlo simulation, VDT converts qualitative and quantitative project design metrics into irreducible, mathematical distributions of outcome. Specifically, the system describes outcome measure distributions using average results and variances that characterize the model's degree of certainty. For example, VDT does not predict a single quantity of information exchange requests, but instead states a simulated average and variability.

Furthermore, VDT does not attempt to model actors' midstream monitoring of, and intervention in, project performance. Instead, the system predicts the behavior that would develop if the organization and process were to proceed as it was initially directed to. For example, VDT may calculate a vastly extended schedule, whereas real managers would likely observe the developing problems and attempt to intervene (such as by hiring additional workers).

Because VDT measures likely propensities, rather than certain outcomes, we interpret the system's performance measures to characterize the degrees of *risk* associated with different project aspects. For example, when a case shows high cost risk, this means that it is likely to produce large cost overruns unless there are 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. We 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 over whether to proceed with a mission, or to a mission that is needlessly costly, risky, or extended in schedule.

In this paper, we do not consider the cost, quality, or schedule of planned missions, but we do use project behavior 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 [JPL Risk Station Paper]. Our analysis of product risk is distinct from, and complimentary to these efforts.

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 [MEP]. For descriptions of over a hundred organizational risk factors, and related literature reviews, see Ciaverelli [] or Cooke and Gorman []. Important factors that VDT does not evaluate include conformity, which decreases the likelihood that individuals will contradict peers' public, erroneous statements [- Festinger?]. "Groupthink", reduces the likelihood of thorough, critical evaluation of alternatives in a group setting [Janis]. Finally, the "Risky shift" phenomenon, that leads groups to select choices that are more risky than those which any participant would individually choose [Bem]. Each of these organizational factors acts principally to reduce the quality of the selected design.

VDT does calculate several measures that regard risk to the product design. Overloaded or unqualified actors 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. When a simulation shows high project risk, this indicates a propensity for failures in the "System of systems" that involve more than one station. *Functional risk* measures the rate of rework (or design iteration) that is ordered for individual tasks. High functional risk at a particular station indicates that the station's design is likely to be independently faulty. 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 integrated design quality. We can predict overall design quality using VDT by viewing these metrics at an aggregate project level, or we may drill down to characterize the product in detail. For example, elevated project risk at the Power station indicates that other subsystems have not redesigned according to its needs, and a high communications risk at the Cost station suggests 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 tracks the amount of work that backlogs for each actor, and this can cause the sense of time pressure that researchers have shown to cause errors []. Compounding this is the sense of actor frustration that VDT measures as the fraction of information exchange requests that are not granted, the fraction of exceptions that are ignored, and the 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 [], and errors of oversight. In addition, they are more likely to burn out and leave a position, and in complex positions is another risk factor.

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 should serve a routine strategic function only if it is effective both in optimal conditions and under foreseeable organizational and other variations.

We ran an intellective VDT experiment that excludes many team-specific factors and found it to preliminarily demonstrate stability in the project design. 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 we have not conducted a complete sensitivity analysis, our more generic experiment shows sufficiently similar outcomes to the tailored model that we view the project design robust within a nominal range of staffing and task variations.

Process Risk

We consider three measures of *process risk* that anticipate the perceived efficiency of the design study project. These are the cost, schedule, and structural stability of the simulated design project. Our VDT model uses the total work volume among all engineers and supervisors to represent the *cost* of an ICE design project. Figure 3 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 in contingency with project performance). Although VDT calculates detailed schedules including average start and finish times for each station's task, we compare alternative cases using the *total project schedule*, or time between execution of the first and last work items. For structural stability, we use the same technique as described under organization risk.

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. As projects become more technically complex and dynamic, we find that actors of superior knowledge or technical skill come to handle organizational deficiencies in work procedures and alternative sets.

VDT is calibrated with a broad range of academics' and professionals' project study experiences, and it has made some strikingly accurate predictions of project performance [Lockheed, others?]. 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 actors engaged in interdependent tasks (or through manually scheduled meetings). Our Team-X model using the current, standard version of

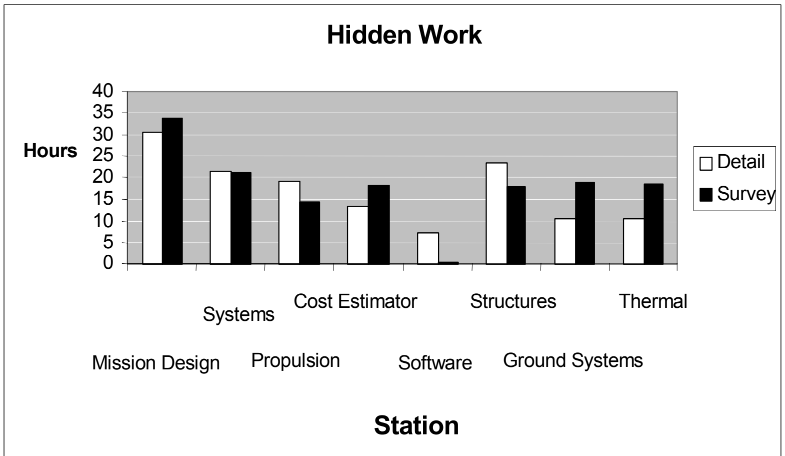

Figure 2: "Hidden work" consists of coordination and rework activities that most software systems and less sophisticated human planners fail to account for. This chart contrasts the hidden work reported in a "Survey" of Team X with the "Detail" hidden work that the VDT simulator predicts. The differences 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.

VDT[3] matches ICE's common, purely hierarchical exception-handling processes from station, to facilitator, to proposal manager.

As technology accelerates, it becomes increasingly difficult for organizational 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 [Contractor]. In our developing theoretical model, organizational managers continue to consult on preferences, but actors locate and retrieve procedural expertise from a distributed network of actors 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 [Diane Bailey's new paper on CEs vs. EEs]. 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.

We compare traditional and knowledge-network based exception handling by first reviewing the simulated (VDT) authority hierarchy results in increased detail. Our simulation does not currently exhibit the network-based exception-handling phenomena that are becoming increasingly common in knowledge work. We contrast this against the work volumes surveyed at JPL. These values incorporate the hierarchy and the technical information flow among peers that characterizes an effective ICE knowledge network.

Although we 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, we alert organizational designers who are steeped in traditional theory to the danger of underestimating the

[3] SimVision 3.11

coordination load that technical experts will experience in decentralized knowledge-based projects such as ICE.

Although management plays an important leadership role in ICE, at JPL we 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 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, we require additional data points 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). Our current result nevertheless reinforces 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.

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 01, and Burton 01]. By grounding a computational model explicitly in a theoretical framework, researchers can explore complex ramifications of a 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. Following the tradition of mathematical proof, when a model of theory produces a recognizable pattern of results, we interpret this and make a new claim. In a perfect world, if the new hypothesis is shown to be false, the model's theoretical premises are disproved (a "proof by contradiction").

At this time, however, model based theory generation is new to domains as complex as project design. In this paper, we apply the technique in its most common modern form- as an engineering method that relies in part on intuition and external observation to validate its claims. Therefore, we accompany our model analysis with intuitive descriptions as well as observational data.

> *"In their anxiety to be scientific, students of psychology have often imitated the latest forms of sciences with a long history, while ignoring the steps these sciences took when they were young"*
>
> *-Psychologist Solomon Asch*

The recent expansions of particularly compatible social science theories and analytic techniques are creating an exciting time for computational organizational modelers [March, and Burton, in Lomi and Larsen 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, sometimes alternatives may be introduced directly to the organization. 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 cases [Kunz et al 1998, ACM; Jin et al 1995, Levitt 1996, Levitt et al, Management Science]. 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 methodology and confidence as is demonstrated on today's automobiles **[Bridges text]** In VDT, for example, we can select from a list of alternative intervention scenarios, and simultaneously compare the results of multiple cases. By weighing actor backlog and other results between alternative cases, VDT users are able to 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 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, actor per station
- An unanticipated project scope extension was not included
- Limited distinction between rework and design iteration

NEXT STEPS

Evolutionary organizational theorists would predict that if ICE performance were viable, it would be widespread. The system perspective we present in the introduction suggests that this apparent conflict may result from a careful balance of factors that aren't 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.

We are designing a computational experiment to investigate this issue by calculating the impacts of each enabling factor from Table 1. We hope that this analysis will more clearly illuminate the interactions between enabling factors and explain:

1. Can a single calibration of the VDT engine simultaneously demonstrate ordinary teams' performance and that of Team-X?
2. Are intermediate states, in which some, but not all enabling factors are satisfied, better or worse than traditional practice?
3. How precipitously does performance drop off when enabling factors are reduced in strength?
4. Is there a sequence of interventions that leads from traditional conceptual design to ICE behavior without reducing performance at any step?
5. How do organizational risk properties change under these conditions?
6. Is there a tightrope of high performance between tradition and ICE that involves simultaneous, gradual improvements in the enabling factors?
7. Do certain intuitive compound factors, such as collocation, match theoretical predictions, and do they complement one another as interventions? [Tse Tse Wong and Richard Burton, CMOT]

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