Observation, Theory, and Simulation of Integrated Concurrent Engineering: Grounded Theoretical Factors that Enable 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,

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

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 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.

THE ICE METHOD AT NASA/JPL

In hundreds of projects over eight years, 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 funding2. 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 Phases A through D: Preliminary Analysis, Definition, Design, Development, and Operations [NASA 1995]. [Match up names]

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.

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]. 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.

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].

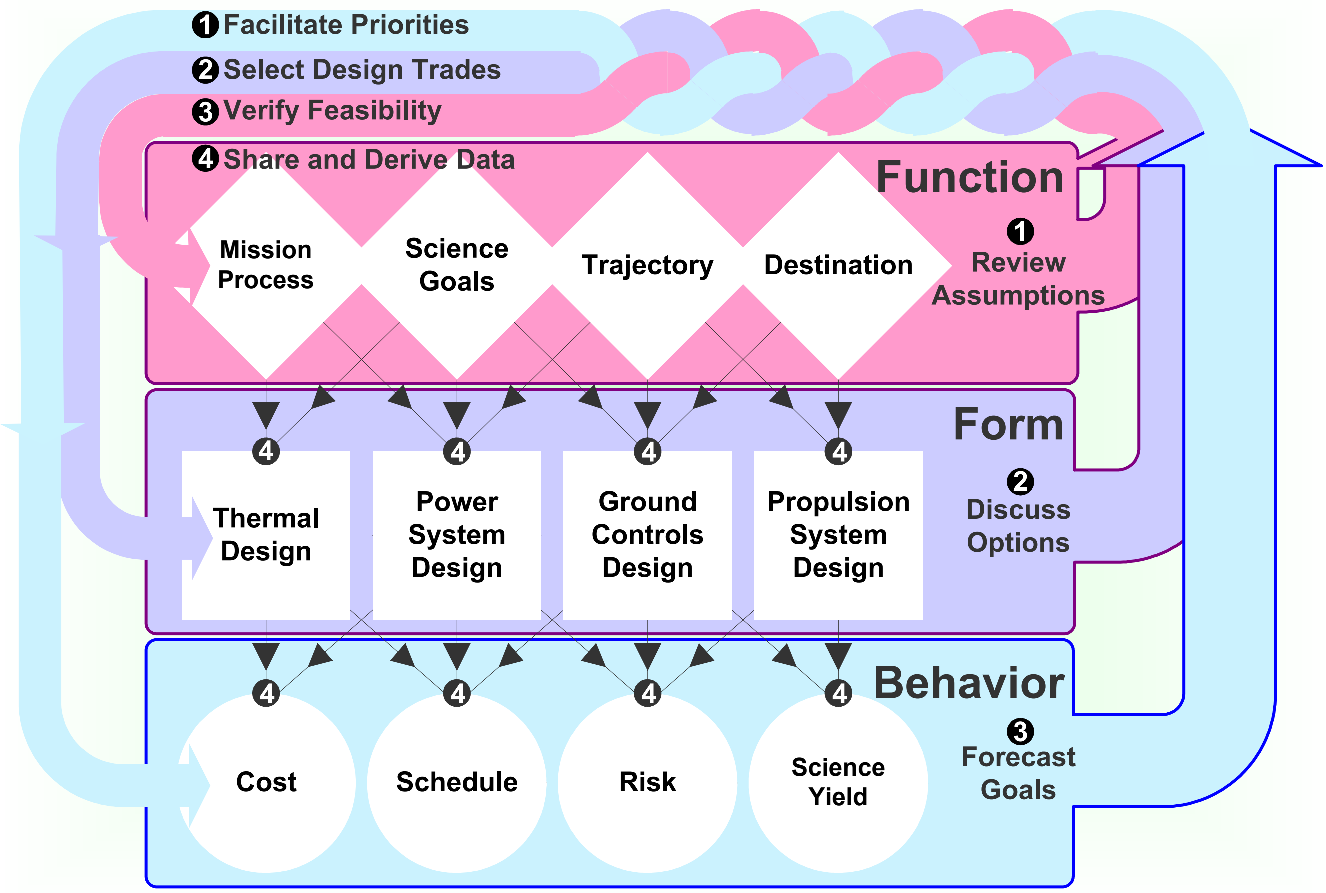

Figure 2 Team-X Schematic Each Team-X "Chair" engineers a component of mission function, design form, or anticipated project behavior. They coordinate using four interdependent processes: Facilitator-mediated tracking of design conformance to goals; "Sidebar" agreements on design trades; Functional review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

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.

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 ACM], although a rough simulator evaluation of this phenomenon's performance impact by [] (year) 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.

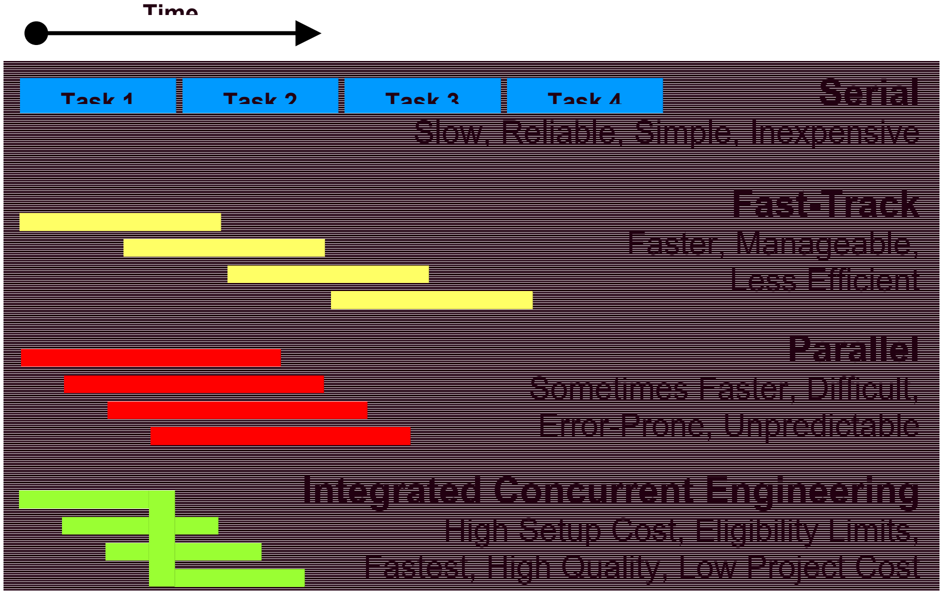

Figure 3 Levels of Parallelsim This diagram shows four tasks arranged with increasing parallelism. Projects under increasing pressure to meet tight schedules often overlap tasks that were once completed serially. Compressing schedule in this way is costly, difficult, and places increased risk on the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

Figure 3 illustrates the differences 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 activities 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 discipilines 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

The subject of this paper, 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 applications, such as ICE.

In modern times, 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 year]. 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 exist3, 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 changing. Scheduling too much parallelism can be counterproductive and risky.

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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].

ICE ENABLING FACTORS

Critical Path Method

Even the humblest of project models offers 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. 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 [CPM- Moder? and Philips]. Tasks "On the critical (or longest) path" will extend total project schedule if delayed, and these activities receive the greatest management attention and resource allocation priority.

A project is considered "Serial" when each task is performed in turn, with only one 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 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

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 compliance with that request is termed "coordination latency". Coordination latency is especially important in interdependent design iteration 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 work volume registers virtually no change. Teams are liable to retrospectively blame individual respondents and transactions for the project's delay unless they are trained to pay attention specifically to the systematic causes of response latency.

Latency in ICE

Because ICE sessions condense project timelines by an order of magnitude, they correspondingly amplify the significance of schedule delays. 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 were traditionally.

We observe 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 easily explains acceleration by orders of magnitude.

We 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 ten fundamental enabling factors Table 1 must 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.

Critical Factor	Success Target	Failure Modes	Team-X Solutions
Structure Independence (Diversity, Load, Differentiation, Urgency, Interdependence)	**High**: allow design task work to proceed without frequent management oversight.	Delays for managerial decision-making or approval; Avoidable 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	Pre- and post-sessions offload what cannot be performed in parallel; Decision support tools accelerate critical path tasks
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
Communications Media 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
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

Critical Factor	Success Target	Failure Modes	Team-X Solutions
Organizational Hierarchy	**Flat**: No organizational barriers or management overhead	Decision making slows awaiting exception resolution by overburdened or multi-tier management	One facilitator, no managers; Management responsibilities distributed; Tools and collocation magnify effectiveness
Psychology and Culture	**Egalitarian yet Intense**: Actors respect co-developers 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 goal metrics
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**: Actors 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; Projection screens; 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	Unrefinable and coarse, or excessive levels of detail cause confusion or excessive management effort	Careful design of the project ontology implemented in ICEMaker, plus the simple (Excel-based) ICEMaker database implementation

Table 1: Factors that enable Integrated Concurrent Engineering. In our judgment, each factor must be well managed to achieve high performance ICE; A shortcoming in any factor risks significant coordination latency and therefore an ineffective or slow engineering design process.

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. We are currently designing a suite of simulations to explore which changes may be safely performed in isolation, and which must be performed in concert. For the time being, 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.

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 we list. For example, collocation provides a pooled communications topology and a closed information network, while enhancing focus, communications richness, and an intense yet egalitarian culture. The Team-X shared database technology reduces process equivocality and enhances communications richness and fidelity. "Structure Independence" is a particularly subtle compound factor for which we offer specific guidance.

Specific Sources of Latency

Activity Interdependence

Figure 3 illustrates the different fundamental 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 completion date 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. Fast-tracked projects start electrical work once a section of the site is framed, and sheetrock the project immediately behind the electrical team. Design projects often attempt to execute tasks entirely in parallel, executing them all at the same time. Because each tasks is dependent on information that collaborators are constantly changing, this is highly challenging to coordinate. In some cases, dependencies are so fundamental that it is not possible to parallelize tasks.

In ICE, a multitude of reciprocally interdependent tasks execute in parallel without producing an unmanageable coordination volume. The ICE design sessions employ the most accelerated approach, in which all work tasks execute simultaneously.

Figure 4 illustrates this dynamic using VDT simulation results. We created a team of sixteen virtual engineers with two alternative management structures: a two-tier hierarchy in one case, and a solitary manager in another. We then varied the degree of overlap, and corresponding coordination load, among sixteen corresponding tasks. For both hierarchies, cost and risk (as measured by work hours and coordination success rates) increase with overlap's increased coordination volume. For an ordinary hierarchy, a limited amount of fast-tracking also improves schedule. However, when approaching parallelism, the engineers become unable to handle the increased coordination load. We found that the flat hierarchy is cheaper than two-tier management for less overlapped projects, but overlapping over a dozen tasks produces more exceptions than one manager can handle.

Real-world projects vary, and the VDT model would require calibration to assess the exact levels at which these phenomena occur. Nevertheless, these two challenges are widely recognized for traditional organizations, and it is particularly mysterious that ICE surmounts them both simultaneously. How can sixteen interdependent engineers handle their coordination loads, while keeping exception handling at a level that a single facilitator can manage? We believe the key to this is a coordinated program of latency reduction.

Organizational Hierarchy

A project's authority system ensures that participants know the tasks they must execute and the organization's goals for their performance. We believe that the traditional authority system, based on a multilevel management hierarchy's great information processing power, cannot support 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]. 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]. 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.

We 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**]**. 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, we 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, George,] because ICE distributes the traditional responsibilities not only to the facilitator, but to others as well. We 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]. Managers need not conduct the typical status report meetings, because the ICE facility provides an automated, persistent display of aggregated team members' 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 ICE requires [Nasrallah et al 2003, Nasrallah 2004]. It demonstrates with mathematical queuing theory that imposing structure on actors' attention- through management, for example- improves significantly (by up to 40%) upon long-term, naturally emergent organizational efficiency only under precise circumstances. We believe that setting realistic expectations and budgeting for ICE's learning curve can provide enough time for IVA's long-term results to apply.

According to this analysis, an ICE application should satisfy one or more of the criteria that Nasrallah et al identify, and that we 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 (when

Pareto optimality equals global optimality). We believe that ICE can support these projects.

In contrast, other projects 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 management 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.

Goal Congruence

In ICE, egalitarian culture and respectful individual personalities must govern conversational initiative based on technical concerns, instead of rank and charisma. 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 from functional managers that reside outside the ICE session.

Alternate Factor	Target	Factor Definition
Diversity	High	The number of independent skill types possessed by parties in the network
Interdependence	Low	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	The contrast in skill levels between the most skilled and the least skilled parties for a given skill type
Urgency	Low	The rate at which pending work becomes useless if not completed
Load	Medium- Low	The demand for work relative to resources

Table 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 because its diversity is high- each participant employs a unique discipline. We argue that ICE cannot accommodate projects that fail this test, and that require a large amount of imposed management structure.

A crisis of respect can introduce considerable latency. Because of the high interdependence among design variables, the coordination that is necessary to resolve any preferential conflict or indeterminacy could delay the entire project considerably. 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 long latency of the stations' traditional home organizations**.** Even under the best conditions, any one of these occurrences 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 [Originator, Williamson, Milgrom and Roberts]. For example, an ICE organization must carefully police itself for crises of professional esteem and conflicts of interest. In a public conversation, we 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.

The requirement for congruent goals limits 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. Our community includes two structures that lack goal congruence but match many other ICE characteristics: Team-I at JPL [Ben Shaw] and ReVeL-3 at Stanford []. Preliminary observations indicate that goal clarification exceptions emerge frequently during these projects, 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 chaotic environment is intolerably strenuous. 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 ACM], but it also psychologically drains participants and motivates Team-X to limit design sessions' duration. The ICE experience of excitement and community in many ways resembles deindividuation [], 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 this last prediction [].

The flat hierarchy also has a psychological impact on individual performance. Even distinctions as inconsequential as eye color, when brought to attention, can divide otherwise egalitarian communities [school study from social psych]. A "superordinate" or unifying goal of greater perceived importance can nullify this type of unwarranted antagonism however [Sherif]. Research has shown that the best team performance occurs when workers are not only motivated but also share personal goals [pitchfork]. Compared with separation into different departments, focusing the ICE team's attention on shared goals should improve group cohesion and therefore enhance performance. ICE sessions lack a common polar 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 the each position's consolidation of technical skills provides more organizational power [HBR on Power] and opportunities to "Spin" information (an abuse of uncertainly absorption- see) or "Hold-up" the team [GM die casing hold-up articles].

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

ICE teams must be wary of groupthink [], which can accelerate the process but reduce quality by limiting the thorough and critical evaluation of selected alternatives. They must also watch out for the "Risky shift" phenomenon [Bem et al 1965] that can produce riskier team choices than individuals would select. However, these hazards of collective decision-making are somewhat offset 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], 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]. For example, choosing a child's gift can be equivocal, while identifying the color of the tenth car to arrive at an intersection is merely uncertain.

	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

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

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. We predict that new ICE application designers must resolve in advance any indeterminacy in methods and solutions' required levels of granularity, fidelity, and scope. This may involve advance enumeration and certification of technical parameters, or establishment of a timely and reliable resolution process.

Spanning Information Networks

When a traditional engineering project requires knowledge that lies outside participants' ken, it may comfortably leverage outside technical resources. An ICE team cannot afford this because it incurs a traditional organization's response latency. Even though Team-X keeps an expediter on hand to ensure rapid follow-up in these circumstances, because of projects' high task interdependence, a single instance jeopardizes a design session's schedule.

The ICE 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).

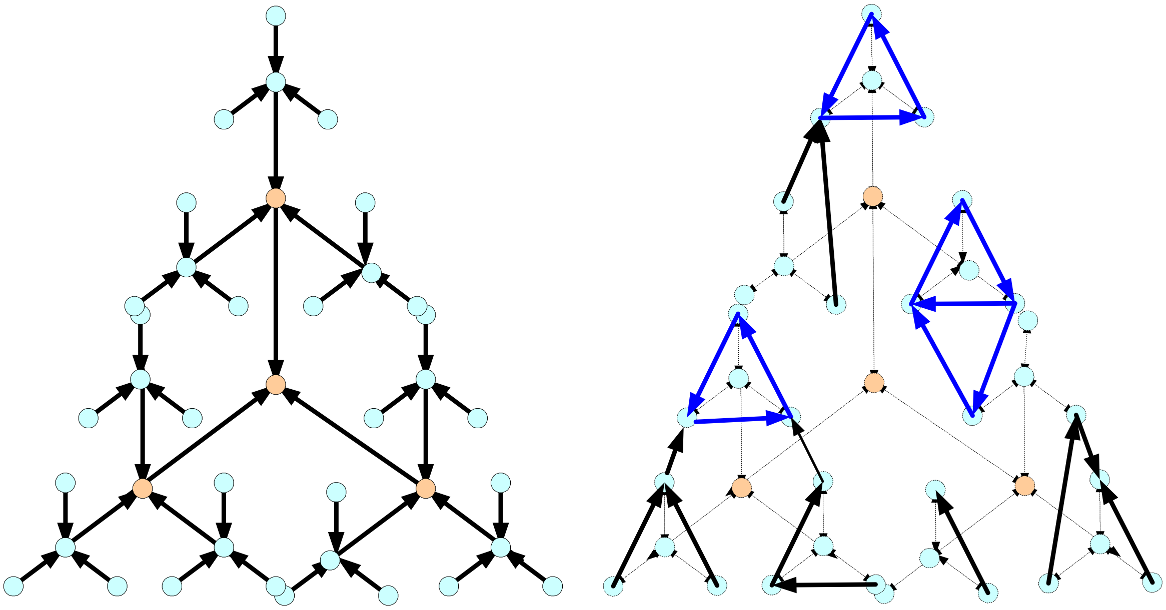

Figure 5: The graph at left shows a typical hierarchy of traditional information demand- a flow that is opposite that of decisions. Laying the traditional 'org chart' in this format, with senior managers encircled by their subordinates, facilitates the cognitive leap from tree to network information flow (at right). On the right is a typical information flow mandated by the task interdependence and the expertise of organizational actors. Routine interdependence produces cycles that motivate organizational adaptations such as group communications, integrated concurrent engineering, and elimination of managerial bottlenecks.

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 actor (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. We diagram this model in Figure 5.

One worst-case scenario emerges when many dependencies stretch across the decision dependency network, and cycles among these two-person "arc" relations manifest. 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 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, and it compounds its very causes. Similar cycles and unreasonably long paths through the dependency network magnify latency to produce endless delays in collaborative engineering, phone trees, and bureaucracies [Eppinger (DSM)].

ICE teams diagnose cyclical interdependencies by observing multilateral interdependence in a shared workspace and formulating a mutually agreeable solution. The "massively parallel" Team-X solves this problem 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, we view this process as encapsulating a subset of the graph that contains cycles into a "sidebar node".

This 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. In spite of contrary hopes and expectations [Su and Park '03], JPL has found that even the highest end videoconferencing technologies currently do not yet adequately substitute for the collocation of core engineers under ICE. Because there are multiple knowledge networks in effect (one for each domain of engineering), we conjecture that ICE requires support for the activation of multiple cycles in communication support. A zero-latency, life-size HDTV communication channel between two collaborating teams of engineers provides a global broadcast mechanism that transcends location boundaries, but it does not enable multiple, simultaneous, impromptu group communications [Mark and DeFlorio].

Instead, voice loops like those commonly used in space mission operations [DVIS] may 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, Mobility may not be an issue at mission control, but ICE developers must either support user mobility (presumably through headsets) or sacrifice a key indicator of project status [Mark 2000].

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 unconditionally release the highly qualified individuals who can perform in ICE projects. Unless a team member can temporarily delegate or suspend his or her 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. This mechanism, combined with the maturity of the product, allows the advance specification of protocols, and transfers information at virtually no cost of precision, time, or effort. Gestures and facial expressions offer improved fidelity to collocated groups. We have observed more complex, but similarly rapid and precise media at Team-X including projected spreadsheets, 3D craft structure and trajectory visualizations, and hand-drawn art.

REMARKS ON ICE

Many aspects of JPL ICE sessions' product, organization, process, and environment are distinctive, modern, dynamic, and resistant to conventional intuition. We 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. We have integrated and extended extant organizational theories in an intuitive manner to enable a more detailed and broadly applicable analysis.

We have drawn attention to and shed light upon two principles of knowledge work. The first is that modern organizations supply four distinctive elements from the general rational framework: beliefs, alternatives, preferences, and procedures (or decision rules). 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.

We offer coordination latency as a unifying, intuitive, explanatory principle. This latency theory indicates that all collaborative arrangements operate at a readily quantifiable level of efficiency and reliability. We suggest that every organization can benefit from an audit of individual latency sources, and, perhaps, continual (if statistical) tracking. When compared with traditional organizations, we 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 what they need as soon as they need it allows the stations to move forward at a greatly accelerated, synchronized pace. ICE is the "Just in Time" of knowledge work, in that it supplies four simultaneous information flows with infinitesimal latency ("lead time") and high micro-scale reliability ("service level").

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, we assert that a principal consideration for all of these alternatives should be the reduction of latency. We 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, we 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 we 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.

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BIBLIOGRAPHY

Asch, S.E. 1987 (original work published 1952) “Social Psychology”. New York: Oxford University Press

Bem, D., M. Wallach, and N. Kogan 1965 “Gropu Decision Under Risk of Aversive Consequences” Journal of Personality and Social Psychology, 1(5), 453-460

Benjamin, J. and Pate’-Cornell, M.Elizabeth 2004 “Risk Chair for Concurrent Design Engineering: Satellite Swarm Illustration” Journal of Spacecraft and Rockets Vol. 41 No. 1 January-February 2004

Burton R and Obel B. 2004 “Strategic Organizational Diagnosis and Design: Developing Theory for Application 3rd Edition”. Boston: Kluwer Academic Publishers.

Carley, K. 1996 “Validating Computational Models” Working paper prepared at Carnegie Mellon University

Chachere, J., Kunz, J., and Levitt, R. 2004, "Can You Accelerate Your Project Using Extreme Collaboration? A Model Based Analysis" 2004 International Symposium on Collaborative Technologies and Systems; Also available as Center for Integrated Facility Engineering Technical Report T152, Stanford University, Stanford, CA

Ciavarelli, A. 2003 "Organizational Risk Assessment" Unpublished manuscript prepared at the Naval Postgraduate School

Cooke, N., J. Gorman, and H. Pedersen 2002 "Toward a Model of Organizational Risk: Critical Factors at the Team Level" Unpublished manuscript prepared at New Mexico State University and Arizona State University

Covi, L. M., Olson, J. S., Rocco, E., Miller, W. J., Allie, P. 1998 "A Room of Your Own: What Do We Learn about Support of Teamwork from Assessing Teams in Dedicated Project Rooms? Cooperative Buildings : Integrating Information, Organization, and Architecture. Proceedings of First International Workshop, CoBuild '98, Darmstadt, Germany, February 25-26, Norbert A. Streitz, Shin'ichi Konomi, Heinz-Jürgen Burkhardt (eds.). Berlin ; New York : Springer: 53-65.

D. B. Smith, "Reengineering Space Projects", Paris, France, March 3-5, 1997.

D. Smith, and L. Koenig, "Modeling and Project Development", European Space & Research Contre, Noordwijk, The Netherlands, November 3, 1998.

Eisenhardt, K. 1989 "Building Theories from Case Study Research", Academy of Management Review Vol. 14 No. 4 532-550

Eisenhardt, K. 1993 "High Reliability Organizations Meet High Velocity Environments: Common Dilemmas in Nuclear Piower Plants, Aircraft Carriers, and Microcomputer Firms" In K.H,. Roberts (Ed.) New Challenges to Understanding Organizations New York: MacMillan, pp. 117-136

Erickson, I. 2004 "Extreme" Unpublished manuscript prepared at Stanford University

Galbraith, J. R. (1977), Organization Design. Reading, MA: Addison-Wesley.

Garcia, A., Kunz, J., Ekstrom, M., and Kiviniemi, A. 2003 "Building a Project Ontology with Extreme Collaboration and Virtual Design and Construction" Center for Integrated Facility Engineering Technical Report T152, Stanford University, Stanford, CA

Glaser, B. and A. Strauss 1967 "The Discovery of Grounded Theory" Chicago: Aldine

Heath, C., Luff, P. 2000 Team Work: Collaboration and Control in London Underground Line Control Rooms. Technology in Action, Cambridge, Cambridge University Press: 88-124

Howard, R. and Matheson, J. (eds.) 1983 *Readings on the Principles and Applications of Decision Analysis*, Decision Analysis, Strategic Decisions Group, Menlo Park, CA

J. Leigh, A. Johnson, K. Park, A. Nayak, R. Singh, V. Chowdhry, "Amplified Collaboration Environments," VizGrid Symposium, Tokyo, November 2002

J. Smith, "Concurrent Engineering in the Jet Propulsion Laboratory Project Design Center", Society of Automotive Engineers, Long Beach, CA, U.S.A., June 4, 1998.

Janis, I. 1982 "Stress Attitudes, and Decisions: Selected Papers" New York, Praeger Publishers

Jin, Y.; R. Levitt; T. Christiansen; J. Kunz. 1995. "The Virtual Design Team: Modeling Organizational Behavior of Concurrent Design Teams," International Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol.9, No.2, (April) 145-158,.

Kunz, J.; T. Christiansen; G. Cohen; Y. Jin; R. Levitt. 1998. "The Virtual Design Team: A Computational Simulation Model of Project Organizations," Communications of the Association for Computing Machinery, (November) pp.84-92.

Levitt, R. 1996. “Organizational Analysis and Design Tools: State of the Art,” First International Conference on Computational and Mathematical Organization Theory, Monterrey, Mexico (October)

Lomi, A. and E. Larsen, 2001. Dynamics of Organizations, AAAI and MIT Press

Luce, R. and H. Raiffa 1990 “Utility Theory” In Moser, P.K. (Ed.) Rationality in Action: Contemporary Approaches (pp. 19-40) Cambridge University Press: New York, NY

Marais, K., N. Dulac, and N. Leveson 2004 “Beyond Normal Accidents and High Reliability Organizations: The Need for an Alternative Approach to Safety in Complex Systems” Working paper prepared at the Massachusetts Institute of Technology

March, J. G., Simon, H. A. (1958) Organizations. New York, John Wiley & Sons, Inc

March, James G. A Primer on Decision Making: How Decisions Happen. New York: Free Press, 1994.

Mark, G. and DeFlorio, P. 2001 “An Experiment Using Life-size HDTV” *Proceedings of the IEEE Workshop on Advanced Collaborative Environments*, San Francisco, CA

Mark, G., 2002. "Extreme Collaboration" Communications of the ACM, Volume 45, Number 6 (June), pp. 89-93.

Mark, G., Abrams, S., and Nassif, N. 2003. “Group-to-Group Distance Collaboration: Examining the ‘Space Between’”. *Proceedings of the 8th European Conference of Computer-supported Cooperative Work (ECSCW’03)*, 14-18. September 2003, Helsinki, Finland, pp. 99-118.

Maule, A. and A. Edland 1997 “The Effects of Time Pressure on Human Judgment and Decision Making” in R. Ranyard, W. Crozier, & I. Svenson (Eds.) Decision Making: Cognitive Models and Explanations (pp. 189-204) New York: Routledge

Meshkat, L., and Oberto, R. 2004 “Towards a Systems Approach to Risk Considerations for Concurrent Design” Working paper prepared at the Jet Propulsion Laboratory, California Institute of Technology

Monge, P. R., & Contractor, N. S. (1999). Emergent communication networks. In L. Putnam & F. Jablin (Eds.) Handbook of organizational communication (second edition). Newbury Park, CA: Sage.

NASA 1995 “NASA Systems Engineering Handbook”, National Aeronautics and Space Administration

Nasrallah, W.; R. Levitt, P. Glynn. 2003. “Interaction Value Analysis: When Structured Communication Benefits Organizations” Organization Science forthcoming in 2003

Olson, J. S., Covi, L., Rocco, E., Miller, W. J., Allie, P. 1998 A Room of Your Own: What Would it Take to Help Remote Groups Work as Well as Collocated Groups? Proceedings of CHI’98: Conference on Human Factors and Computing Systems. Los Angeles, California, April 18-23, 1998. New York, ACM Press: 279-280.

Orasanu, J. “Organizational Risk Model” Working paper prepared at NASA Ames Research Center

Paté-Cornell, M.E., 1990 "Organizational Aspects of Engineering System Safety: The Case of Offshore Platforms," Science, Vol. 250, November 1990, pp. 1210-1217.

Murphy, D.M. and M.E. Paté-Cornell 1996, "The SAM Framework: A Systems Analysis Approach to Modeling the Effects of Management on Human Behavior in Risk Analysis", Risk Analysis, Vol. 16, No. 4, pp.501-515.

Perrow, C. 1984 “Normal Accidents: Living with High-Risk Technologies” New York: Basic Books

Perrow, C. 1994 “The Limits of Safety: The Enhancement of a Theory of Accidents” *Journal of Contingencies and Crisis Management*, 2, (4), 212-220

Powell, W. and DiMaggio, P. (Eds.) 1991 “The New Institutionalism in Organizational Analysis” Chicago: University of Chicago Press

Reason, J. 1997 “Managing the Risks of Organizational Accidents” Brookfield: Ashgate Press

Roberts, K. 1990 “Managing High-Reliability Organizations” *California Management Review*, 32, (4), 101-113

Sercel, J. 1998 “ICE Heats Up Design”, Aerospace America July 1998

Teasley, S., Covi, L., Krishnan, M. S., Olson, J. S. 2000 How Does Radical Collocation Help a Team Succeed? In Proceedings of CSCW’00: Conference on Computer-Supported Cooperative Work. Philadelphia, Pennsylvania, December 2-6, 2000. New York, ACM Press: 339-346.

Teasley, S., Covi, L., Krishnan, M., Olson, J. 2000. “How Does Collocation Help a Team Succeed?” ACM Conference on Computer Supported Cooperative Work.

Thompson, J., 1967. “Organizations in Action: Social Science Bases in Administrative Theory”, McGraw-Hill, New York

Tversky, A. and D. Kahneman 1974 “Judgment Under Uncertainty: Heuristics & Biases” in D. Kahneman, P. Slovic, &A. Tversky (Eds.) *Judgment Under Uncertainty: Heuristics and Biases*. Cambridge: Cabridge University Press

Wall, S. “Design Process Enhancements for Planetary Missions”, 4th International Conference on Lowcost Planetary Mission, Maryland, USA, May 2, 2000.

Wall, S. “Reinventing the Design Process: Teams and Models”, IAF, Specialist Symposium: Novel Concepts for Smaller, Faster & Better Space Missions, Redondo Beach, California, USA, April 19-21, 1999

Wall, S., D. Smith,, L. Koenig, and J. Baker, “Team Structures and Processes in the Design of Space Missions”, MTG: 1999 IEEE Aerospace Conference, Snowmass at Aspen, CO, U.S.A., March 6-13, 1999

Scott, W. R. 1998 “Organizations: Rational, Natural, and Open Systems (4th Edition)” New Jersey: Prentice-Hall

Weick, K., Roberts, K. 1993 Collective Mind in Organizations: Heedful Interrelating on Flight

Weick, K.E. and K. Sutcliffe 2001 “Managing the Unexpected: Assuring High Performance in an Age of Complexity”, Jossey-Vass, San Francisco, CA

Wheeler, R., J. Hihn, and B. Wilkinson “Distributed Collaborative Team Effectiveness: Measurement and Process Improvement” Working paper prepared at the Jet Propulsion Laboratory / California Institute of Technology

Witt, K., Giorcelli, R., Darrah, M., Ives, B. 2004 “DEVISE: A Collaborative Virtual Environment for Integrated Concurrent Engineering”, 2004 International Symposium on Collaborative Technologies and Systems

Zajonc, Robert B. “Social Facilitation” Science 149, July 16, 1965 269-74