The Role of Reduced Latency in Integrated Concurrent Engineering

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The Role of Reduced Latency in Integrated, Concurrent Engineering

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Abstract

Since 1996, multi-disciplinary space mission design teams at NASA's Jet Propulsion Laboratory have been using a novel concurrent design approach. This approach creates integrated early phase designs that used to take nine months in about three weeks! To make this possible, the JPL group known as Team-X completes most of its engineering and collaboration work in just nine hours of intensive, technically mediated and socially facilitated group sessions. Since 2004, we have used the JPL methods successfully in teaching Virtual Design and Construction methods for Civil Engineering project design. We call the enabling technically mediated social collaboration process *Integrated Concurrent Engineering* (ICE). Previous research has observed that ICE uses atypical organization, process, and technology, but has not explained why JPL consistently achieves radical schedule compression while others consistently fail. Our analysis suggests the speed of most engineering processes is limited by their *response latency,* the lag time from a participant asking a question to receiving an answer that is good enough to enable further work. We find that typical response latencies ranging from days to weeks cause routine conceptual design projects to stretch out for months or years. In contrast, reliable, exceptionally short response latencies – in the range of a few minutes – can enable the extremely short durations for space mission designs at JPL and for facility design teams using our ICE method. Based on our analysis of the JPL process and our own teaching and user experiences, this paper offers thirteen factors that, when *all* functioning at a high level, enable extremely short response latency of ICE team participants, short design session duration, and high perceived design quality. We view ICE as a "Just in Time" approach to knowledge work, in that it manufactures interdependent design decisions with short latency ("lead time") and high reliability ("service level"). This paper proposes that project managers should establish the specific, measurable objective of very short response latency as both a unifying goal for project teams and a practical metric to describe, evaluate, and manage engineering design collaboration. We propose response latency as a fundamental theoretical factor that (along with task duration, coordination, and rework) determines project duration.

Introduction

Design Team Performance Acceleration

Integrated Concurrent Engineering (ICE) achieves extraordinarily rapid design with a quality similar to or surpassing traditional methods and a lower cost [Smith 1997, 1998; Smith and Koenig 1998; Wall 1999, 2000; Wall et al 1999] [1]. We find that ICE uses: a singularly rapid combination of expert designers; advanced modeling, visualization and analysis tools; a set of consistent social processes, and a specialized design facility to create preliminary designs for complex systems. When compared with a traditional parallel engineering method, successful ICE users reduce project schedule by several orders of magnitude, while substantially improving design cost and maintaining quality standards. Today's pioneers of ICE are in the aerospace and automotive industries, where several closely related methods are termed "ICE", "Extreme Collaboration", 'Concurrent Design Engineering", or "Radical Collocation" [Mark 2002, Benjamin and Pate'-Cornell 2004, Covi et al 1998, Olson et al 1998]. Whereas traditional engineering superficially resembles a government bureaucracy, ICE performs the same work in an environment more akin to NASA's Shuttle Mission Control operations. Figure 1 shows an experienced team performing engineering design in an effective ICE session.

Figure 1: Team-X's Distinctive Method Vastly Accelerates Space Mission Design 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

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[1] We thank Stanford Center for Integrated Facility Engineering, Stanford Media-X, and NASA Ames Research Center for generously supporting this research. With additional thanks, but without explicit description, we leverage observations from similar practices at the Tactical Planning Center of Sea-Land Service Inc., at Stanford's Gravity Probe B Mission Control, and at Stanford's Real-Time Venture Design Laboratory.

necessary, but not sufficient for them to be successful. Photograph courtesy of NASA/JPL/Caltech.

Our research team observed an experienced ICE team at NASA, the Jet Propulsion Laboratory (JPL) Advanced Project Development Team, known as Team-X. 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].

From reviewing observations, theory, survey data, and model-based analysis, we developed a theoretical framework of ICE success factors that explains the remarkable performance as resulting from low coordination latency at Team-X (this framework is the subject of this paper's second half). At the Stanford Center for Integrated Facility Engineering (CIFE), we have used this framework to teach, research, and demonstrate ICE in the building design industry, which is a very different industry from space missions.

Research Goals

This paper presents a theory of *how, why, and in what ways ICE works.* We have the goal to describe, for practical organizational designers, a process performance metric that can help teams understand the limits on their performance today. Previous descriptions of ICE do not derive a broadly applicable and refutable theory explaining fundamental mechanisms of ICE and its behavior. Research on the behavior of ICE and similar projects [Mark 2002, Teasley et al 2000] describes important features of ICE. The JPL cross functional team divides responsibility into 'stations' that each design a portion of the overall mission, such as vehicle configuration, payload, project management, cost, propulsion, and ground support. The team as a whole conducts highly concurrent design by collocating multiple, disciplinary experts for a series of three-hour design sessions.

Methodology

Our claims are based on simultaneously validating theories by comparing them with observations, verifying theories' consistency using computer models [Chachere 2008], and calibrating the results' implications against our initial and new observations. Consistencies among reality, intuition, and formal modeling and simulation explicitly ground the work.

This research had four orthogonal and complementary research elements:

1. *observations* of a very fast (one week) project at JPL,
2. *development of formal yet intuitive theories* that have face validity and offer straightforward comparison with established social science theories,
3. *computer simulation experiment* operationalizing the theory to show emergent implications of foundational micro-theories for projects (in Chachere et al. 2004, Chachere 2008), and
4. *observations* from our own application of ICE to building design at CIFE.

Observation

We visited JPL's Team-X and ethnographically observed three design sessions of a 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.

Theory

Our observations, interviews, and survey use a set of factors that enable radical project acceleration. We explain 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, my theorizing also draws on novel behaviors and relationships observed in ICE practice.

Simulation

Our previous research [Chachere et al 2004, 2005, Chachere 2008] presented three computational project models to describe and predict the performance of an ICE team. That work retrospectively calibrated the Organizational Consultant (OrgCon), Virtual Design Team (VDT), and Interaction Value Analysis (IVA) models to describe our observations at Team-X accurately, and found that the model results are consistent with observed ICE phenomena.

Observation of ICE

ICE at JPL

In hundreds of projects since 1996, Team-X at JPL has developed and applied ICE in short design sessions. Figure 1 shows a photo of a design session in the custom Product Design Center facility. Team-X projects develop initial designs of unmanned, deep space mission that then are evaluated for funding. 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 over five hundred 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.

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

Product

Team-X designs the initial, technical design core for an unmanned, deep space mission proposal. At NASA, this work is known as "Pre-Phase-A," or "Advanced Studies," and it precedes the Preliminary Analysis, Definition, Design, Development, and Operations phases [NASA 1995].

The three horizontal areas in Figure 2 illustrate our decomposition of this work into three specification components: a mission *function*, an engineering design *form*, and predicted *behaviors*. 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.

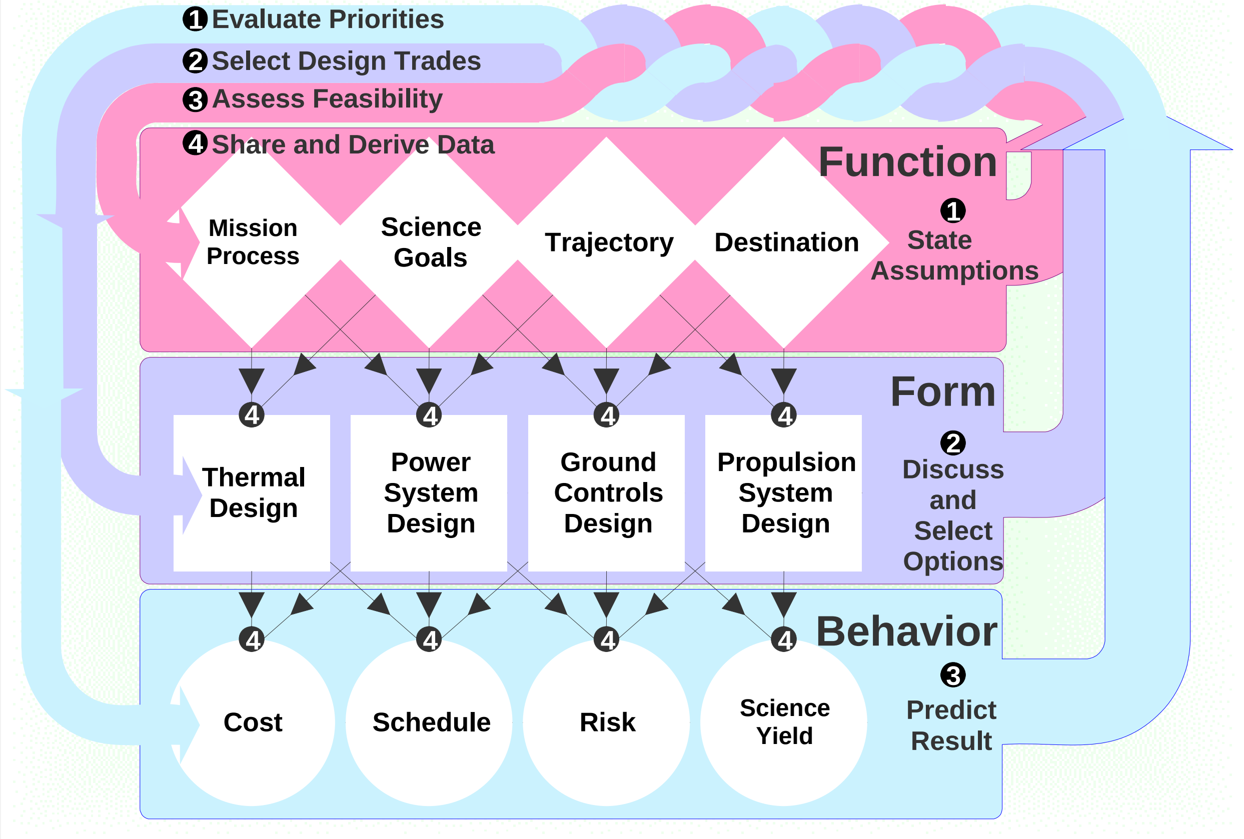

Figure 2: Conceptual Schematic of Team-X Using ICE, Team-X develops mission and system functions, form and behaviors using concurrent processes with very low latency. Each Team-X "station" (depicted as white diamonds, squares, or circles) engineers a component of mission function, design form, or predicted project behavior. Stations coordinate using four interdependent processes: Facilitator-mediated tracking of evaluated design conformance to goals (marked '1'); "sidebar" agreements on design trades (2); Functional review of goal feasibility (3); and automated data sharing of networked modeling and analysis programs and data (4). The figure illustrates only a fraction of the stations and information links at Team-X.

Organization

Team-X includes about eighteen domain experts, a facilitator, and a customer representative. Each of the engineer "stations" is responsible for design decisions within a specific domain "station" such as Power, Propulsion, Cost Estimation, or Trajectory Visualization. Each station states principally the mission function, designs its form, or predicts its behavior, as Figure 2 illustrates. 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, the Team-X organization is flat. Stations have responsibility to develop the function, scope, and behavior for their assigned systems and the integrated physical vehicle, as well as its development and operations organizations and processes. Participants largely work without management guidance or oversight; Instead, the team collectively provides guidance with the help of facilitator oversight. 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 ability to work independently and effectively in the informal, superficially chaotic, high-pressure conditions. Partly because they are psychologically demanding, Team-X limits design sessions to three or four hours. After an eight-hour ICE charrette demonstrating Virtual Design and Construction at Stanford, one participant felt as if "run over by a train" [Garcia et al 2003].

Process

A typical Team-X project requires fewer than five hundred full-time-equivalent (FTE) 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 describe 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 models and analyses 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 initiate their correction [Mark 2002], although a rough simulator evaluation of this phenomenon's performance impact by [Bellamine and Saoud 2002] was inconclusive. Even though the engineers represent several organizational divisions, there are no managers present in the design session. Instead, a single facilitator helps sidebars to form, and directs the group's attention to important developments.

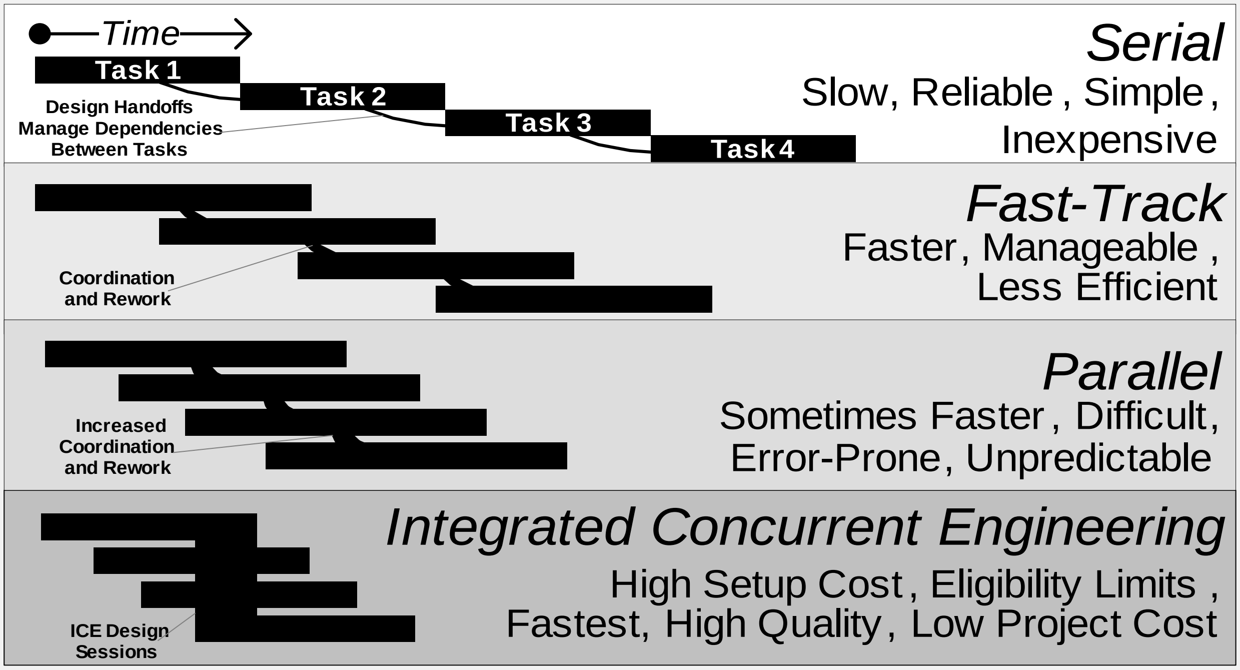

Figure 3: Degrees of Parallelism ICE radically increases task parallelism and operates to facilitate effective and efficient coordination with little waiting and rework. This diagram shows a schematic Gantt bar chart with four tasks arranged with increasing parallelism. Projects under increasing pressure to meet tight schedules often overlap tasks that once executed serially. Compressing schedule in this way is costly, difficult, and risky for teams failing to anticipate the complex interactions between product, organization, process, and technology. Many industries are broadly parallelizing design tasks, but few teams have experimented with ICE yet. ICE represents the most accelerated of these engineering methods, in which the full organization gathers and executes the most interdependent work together. We predict and observe in ICE that the coordination and rework effort equals or exceeds the effort given to direct work. ICE works well when the individual subtask durations are short (a few minutes) and coordination latency is reliably exceptionally short (waits to initiate discussion rarely exceed one minute), and coordination duration is short (a few minutes at most).

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

Technology

Each design participant has a computer workstation and a set of discipline-specific modeling, visualization and analysis tools. The team has a shared database that networks all workstations using a publish-and-subscribe paradigm. The shared database has a generic data schema of nearly four thousand design variables that represent the functional requirements, design choices and predictions of each discipline. Computer systems and facilities personnel support the group’s tasks without actively influencing the designs themselves.

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

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

More specifically, every member of Team-X uses a modeling and prediction application (in many cases implemented as 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

Today, many industries experience dramatic increases in the volume and intensity of competition. Simultaneously with high-level strategies such as the globalization of operations, firms look for ways improve existing operations 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 [1993] synthesized these concepts to help the business community recognize that the work contexts of many firms change more rapidly, and in different ways, than the business organizations and work methods change naturally. Business processes therefore naturally retain some adaptations that were evolved or designed for conditions that no longer exist, and it eventually becomes easier to replace the work methods entirely than to attempt to fix them incrementally. Hammer and Champy's [1993] "Business Process Re-engineering" (BPR) method 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. However, because of the complexities of matching product, organization, process, and tools, BPR efforts frequently overrun budget and, once complete, often fail to meet expectations eventually. For this reason, practitioners and consultants are generally eager to learn what they can from successful BPR applications such as ICE.

ICE results from JPL's successful application of BPR to highly interdependent engineering tasks that today are more commonly performed in parallel using traditional methods. Aerospace is one of many industries in which highly interdependent work practices have adapted by partially overlapping previously serial tasks. Overlapping dependent tasks adds complexity, which leads to coordination, rework, and waiting for information and decisions, because the results of work that would traditionally have been complete may be unavailable or subject to changes. ICE acknowledges the coordination and rework, and it attempts to diminish waiting by facilitating both the effectiveness and efficiency of coordination.

ICE at Stanford

We implemented ICE at the Center for Integrated Facility Engineering (CIFE) to teach, research, and demonstrate ICE for the Architecture, Engineering, and Construction (AEC) industry. Like Team-X, CIFE teams focus on conceptual design, which explores the first engineering-driven design trades using industry-specific computer models. Figure 4 illustrates an ICE session in the first CIFE iRoom, configured primarily using tools already present at our engineering center; CIFE has now moved to a much larger facility designed for ICE sessions specifically.

The Civil and Environmental Engineering Department teaches ICE in classes on computer-based building design and analysis. In the past six years, the department use of ICE grew from two sessions for six students to this year when we will offer around six sessions for a large fraction of our department's students. In multiple ICE sessions, students learn costing, scheduling, organizational design, risk analysis, 3D modeling, 4D construction planning, presentation, and decision making. Teaching and applying these tools together imparts an appreciation for engineering's social and technical interdependencies that students traditionally learn only after graduating to professional practice.

Figure 4 Students Conducting an ICE Session **This picture shows students in a CIFE iRoom. In a two hour session, students build coordinated models of the product, organization, and process, multiple analyses of product, organization and processes, as well as propose and present a summary of the multiple models, analyses, and management findings of the session for customers. Students use tools (3D, schedule, risk, decision, and presentation) and coordination (gestures, voice, smart boards, networked computers, and paper) to address real engineering problems. In two-hour class design sessions, students create**

design deliverables including coordinated design-construction organization models and schedules, 3D and 4D models, and risk assessments.

Theory of Latency

Latency Definition

Critical Path Analysis

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

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

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

Response Latency Analysis

We assume that any high-level task has a series of subtasks, any of which can require information that is not immediately available to the responsible actor. When a task on the critical path requires information, its queries are also on the critical path. The amount of time that elapses between a request for information or action and receipt of a satisficing answer to that request is "coordination latency." Coordination latency becomes especially important for the interdependent tasks that involve a large number of information exchange and exception handling requests. Table 3 uses a simple calculation to illustrate latency's effect on task duration, and to compare that effect with the effect of automation.

Total Task Duration		**Subtask Durations**	
		One Day (Typical)	**One Minute** (Automated)
Coordination Response Latencies	**One Day** (Good)	**40 Weeks** (Typical)	**20 Weeks** (Automated)
	One Minute (ICE)	**20 Weeks**	**3 Hours** (ICE)

Table 3: Task Duration is a Function of Latency and Subtask Durations. This table shows results from a simple calculation of duration for a typical engineering task (such as structural design in AEC or telecommunications hardware design in aerospace). A 40-week task, for example, might comprise 100 one-day subtasks of direct work and 100 one-day requests for information. In this example, direct engineering work and communication latency have the same effect on total task duration. In particular, reducing each engineering subtask to a simple one-minute decision (an ideal for many information technology development efforts) without addressing latency only cuts the total task duration in half. Successful ICE simultaneously reduces coordination latency and subtask duration, leading to a useful design in about a half day, and to a useful integrated design document in a week.

A successful executive at a technologically advanced construction company recently declared 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 such latency, the schedules will grow significantly — while the total direct work volume registers virtually no change. Teams are liable to blame individual respondents and transactions for the project's delay retrospectively, unless they learn to pay specific attention to the systematic causes of response latency.

Because ICE sessions condense project timelines by an order of magnitude, they amplify the significance of latency delays correspondingly. A single hour's latency, while routine and inconsequential under traditional design conditions, can eliminate a significant fraction of an ICE period, waste over a dozen engineers' time, and jeopardize the project schedule. To be effective, therefore, an ICE team must deliver low latency at a very high level of reliability (3-sigma or better!).

Latency Sources

This section uses latency as a theoretical key to unlock 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 fundamental enabling factors in Table 1 must satisfy a corresponding success condition with extremely high consistency. 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 Risks	ICE Solutions
1.	**Subtask Sequencing**	**Parallel** (and Reciprocally Interdependent)	Sequentially dependent design tasks are held up, waiting for others to complete work	Generic & project-specific effort to parallelize tasks; Pre- and post-sessions offload what cannot be parallelized
2.	**Organizational Hierarchy**	**Flat**: No organizational barriers or management overhead that add to latency	Decision making slows awaiting exception resolution by overburdened or multi-tier management	One facilitator, no managers; Management responsibilities distributed
3.	**Task Structure Independence**	**High:** design task work proceeds without frequent management oversight.	Delays for managerial decision-making or approval; Needless underutilization or resource bottlenecks	Culture that enables designer autonomy; frequent, rich and public review of designer choices
4.	**Team Goals**	**Clear and Congruent**: Participants aspire only to project success.	Debates on process, decision flip-flops, inappropriate rework	Culture; facilitator attention; Persistent wall projection of formal goals
5.	**Team Psychology and Culture**	**Collegial** (though intense): Team members respect each other in a high pressure environment	Infighting, over-conservatism, defensiveness; Fatigue	Participant training and selection; Functional organizations support participant authority
6.	**Process Equivocality**	**Low**: Procedures are well understood and accepted	Extended debates about process or priorities	Culture; Experienced facilitator leads process; excellent definition of process, tasks, and task dependencies
7.	**Team Knowledge Network**	**Complete:** Responsible actors for all tasks have requisite knowledge, procedures, options, and authority 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 stations and participants for each design session
8.	**Interpersonal Team Communication Topology**	**Pooled**: Members resolve problems very quickly in groups of two or more	Inability to explain a design choice appropriately causes confusion and delay; personal style detracts from group performance	Team collocation; Persistent wall projection of design predictions; Voice sharing in distributed implementations
9.	**Participant 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 allow constant availability of highly skilled participants

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	Critical Factor	Success Target	Failure Risks	ICE Solutions
10.	**Communication Media**	**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
11.	**Integrated Software and Conceptual Models**	**Semantically rich**: modeling applications of multiple disciplines share their common data, but not their discipline-specific data	Indefinable and coarse, or excessive levels of detail cause confusion or excessive management effort	Interoperable software applications with schemata and semantics designed for quickly, easily, and reliably reading and writing shared data.
12.	**Discipline-Specific Modeling, Visualization, and Analysis Tools**	**Strategic:** Balanced so that all potentially critical-path tasks are accelerated	Manual design tasks bottleneck project schedule	Decision support tools accelerate critical path tasks

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

1. Task Sequencing: Parallel

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

2. Organizational Hierarchy: Flat

In ICE, participants know the tasks they must execute and the organization's goals for their performance. The traditional authority system, based on a multilevel management hierarchy's information processing capacity, has not enabled the fast pace an ICE session demands. As in command centers for military operations and for air traffic, ICE creates and requires flat information exchange hierarchy. This section explains how the need for management direction interacts with the processes of ICE.

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

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

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

Because managers lack the attention to closely supervise multiple engineers simultaneously, ICE relies on participants' independence. The ICE project advances beyond the theoretical limit of seven (plus or minus two) subordinates [Miller 1956] because ICE distributes the traditional responsibilities not only to the facilitator, but to the team. 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, manager customer representative speaks with the team directly, and ensures the consistency of project goals. Facilitators are safely distanced from the functional stations' personnel reviews because, in an open setting, technical skill is a psychologically natural method by which peer groups police themselves [Festinger 1954]. Teams do not conduct typical status report meetings because the ICE facility provides an automated, persistent display of team members' aggregated progress. Finally, participants are trained and authorized to make decisions, according to their own judgment (and subject to review by the entire team), rather than consulting with a manager.

3. Task Structure Independence: High

Interaction Value Analysis (IVA) distinguishes a set of conditions that teams require for a "lightweight" management and informal communication style, like that used in ICE, to be effective [Nasrallah et al 2003, Nasrallah 2004]. IVA uses a mathematical queuing theory and game theory analysis to find that imposing structured communication channels on actors improves organizational efficiency only under a limited set of circumstances, compared to allowing actors themselves to select with whom and when they communicate. Because IVA predicts long-term performance, setting realistic expectations and budgeting for a learning curve may be required to develop an effective ICE team.

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

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

Applying the IVA analysis suggests that ICE teams 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 efficient operations in which Pareto optimality equals global optimality. The latency theory suggests that ICE can support structurally independent projects, if other enabling factors are also present.

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

4. Team Goals: Clear and Congruent

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

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

Even if goal conflicts do not actually manifest, organizations must typically act to mitigate the perceived risk, thus compromising baseline performance [Coase 1937, Williamson 1975, Milgrom and Roberts 1992]. For example, an ICE organization must carefully police itself for crises of professional esteem and conflicts of interest. In a public conversation, 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 of confidence. In another case, publicly resolving a more broadly recognized dispute helped restore the community's confidence in all concerned.

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

5. Team Psychology and Culture: Collegial

One of the most commonly mentioned criteria for Team-X participant selection is that for many, the work environment's chaos is intolerably stressful. Participants are exposed to multiple streams of conversation, and must filter them for key words of interest — without losing productivity on individual tasks. This level of activity provides some error checking [Mark 2002], but it also psychologically drains participants and motivates Team-X to limit design session durations.

When ICE sessions at CIFE are most effective, engineers report a feeling of losing themselves in the work, and when sessions struggle, engineers occasionally require facilitation to focus correctly on the work rather than on other distractions. The ICE experience of excitement and community union resembles deindividuation [Festinger et al 1952], a psychological phenomenon whose effect on design information processing is not known. Theories presented by Zajonc [1965] suggest that the pressure of group scrutiny improves ICE designers' performance but limits their ability to learn on the job. Recent studies by Monique Lambert on transactive memory at Team-X support the latter prediction [Lambert and Shaw 2002, Lambert 2005].

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

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

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

6. Process Equivocality: Low

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

	Clear, Congruent Goals	**Unclear/Conflicting Goals**
Clear Procedures	ICE functions well	Product debates stall ICE
Equivocal Procedures	Process debates stall ICE	ICE may fail entirely

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. This aspect of the latency theory predicts that new ICE applications can only perform adequately if they resolve in advance any indeterminacy in methods and solutions' required levels of granularity, fidelity, and scope. Doing so may require prior enumeration and certification of technical parameters, or establishment of a timely and reliable conflict resolution process.

7. Team Knowledge Network: Complete

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

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

8. Interpersonal Team Communication: Pooled

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 the mathematical theory of graphs, the common lay term "hierarchy" corresponds to a directed graph structure with no cycles. In the organizational theory of networks, each "node" represents an actor (and any tools) that processes information, and arcs represent dependencies. Under this simple mathematical model of decision-making and information exchange, a perfectly balanced hierarchy distributes information effectively and efficiently (in logarithmic time). Figure 6 illustrates this model.

A worst-case scenario emerges even in balanced hierarchies, however, when many dependencies stretch across the decision dependency network, and when cycles among these two-person "arc" relations occur. For example, consider that a spacecraft's power systems engineer relies on propulsion to define requirements, while propulsion in turn relies on on trajectory, and trajectory relies on input from the power systems engineer. Unless the same knowledgeable and attentive manager supervises them all, the team may fail to recognize an endless sequence of ensuing information requests in the dependency cycle. This problem can occur unexpectedly, for example, when two fast-tracked tasks are delayed enough to overlap with a third. Similar cycles and unreasonably long paths through the dependency network can magnify latency to produce endless delays in collaborative engineering, phone trees, and bureaucracies [Eppinger 1991].

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

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

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

9. Participant Focus: Committed

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

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

10. Communications Media: Rich

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.

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 screen-projected spreadsheets, 3D craft structure and trajectory visualizations, and hand-drawn art. The observed diversity of rich and precise media at Team-X supports the latency theory.

11. Integrated Software and Conceptual Models: Semantically Rich

Engineers using separate tools and method require a shared, precise language to ensure the design is consistent. The period required to translate information from one computer system to another, or to determine how data relates between two engineering systems conceptually, is a form of latency. Team-X communicates many design variables among participants formally, through a shared database. Their mature integration method allows the advance specification of data structure and validation, and transfers information at virtually no cost in lost precision, time, or effort during the design session. Furthermore, Team-X investment in building the shared database helps build knowledge over a long period. CIFE integrates data using a shared file system, tool-specific export and import capabilities, and a consensus-building and decision support tool [Haymaker and Chachere 2006, Haymaker et al. 2008].

12. Discipline-Specific Modeling, Visualization, and Analysis Tools: Strategic

ICE requires most stations can conduct direct work rapidly once suitable data are available. Although many stations at Team-X use a direct interface to the shared database, many also use discipline-specific applications such as trajectory and spacecraft configuration models. At CIFE, ICE sessions employ 3D and 4D CAD, scheduling, costing, organizational modeling, and other tools. The suite of tools deployed in ICE must provide each station with the ability to make decisions rapidly once data are available because running in parallel places each station perpetually at risk of becoming the critical path. If an engineering task requires a long or indeterminate period, such as deeply creative thinking, then it can produce decision latency unacceptable in the ICE context.

Observations of Latency, Latency Sources, and Project Quality

This section provides the results of surveys regarding latency sources observed in ICE sessions at CIFE. The 43 survey responses, from participants in 10 ICE sessions over a 3 year period, reflect a roughly one-third response rate for the surveyed sessions. The respondents included undergraduate and graduate students, faculty, and engineering professionals, who typically had participated in few, if any, previous ICE sessions. Although CIFE ICE sessions generally ran better with experienced teams, even inexperienced (but well-instructed) teams performed remarkably like JPL's Team-X in terms of latency sources, latency, and project quality.

Latency Sources Observed in ICE

Figure 3 provides the results of surveys indicating latency sources observed in ICE sessions at CIFE are similar to those observed at Team-X. The results support our claim that ICE sessions at CIFE achieve the targets in critical success factors for reducing latency, as presented in Table 3. Only one measure showed over one-quarter disagreement, meaning that sometimes not all knowledge required for the design task was present. Respondents benefited from the development of ICE capability at CIFE, but far less experience than Team-X possesses, and we believe that more experience in developing the ICE capability increases the consistency in achieving the latency reduction methods' targets. The result of this survey is consistent with the claim that CIFE has consistently met the targets for critical factors proposed to reduce latency in ICE.

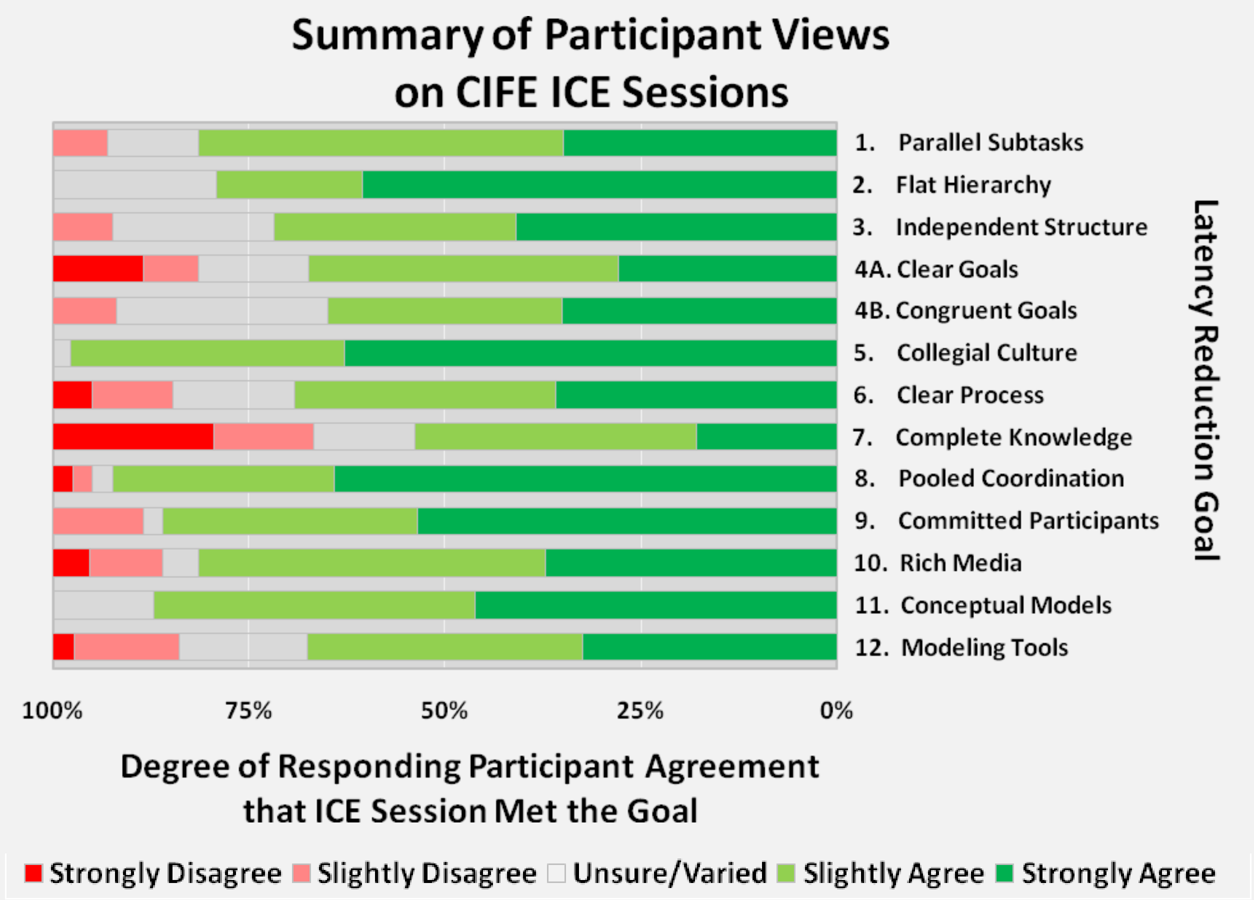

Figure 1: Summary of Latency Sources Observed in CIFE ICE Sessions This figure charts the degree to which 43 participant views of 10 CIFE ICE sessions supported the 12 latency reduction enabling factors this paper describes. Generally, participants found that each of the enabling factors operated at a high level, but not as high as may occur after individuals and teams participate in more sessions and grow in both individual and team experience. At JPL's Team-X, we observed these same project features. We infer that the high level of perceived presence of enabling factors provides evidence for our claim that low latency follows their all the factors being present. We infer that the generally good outcome assessment is evidence for the power of the ICE method for early-phase design in AEC.

Latency Observed in ICE

Table 6 summarizes CIFE ICE participant reports that latency consistently below a handful of minutes, which is orders of magnitude lower than those reported by AEC engineers using traditional methods. At Team-X, we also observed engineers produce response latency ranging from seconds to a handful of minutes by sharing engineering design data in ICE sessions using an integrated database, and by issuing requests verbally to readily available and qualified respondents. These ICE sessions' coordination and rework therefore do not produce the schedule expansion that occurs in traditional teams under ordinary latency conditions. In highly parallel engineering projects, where interdependent design iteration is the norm, this one variable can easily explain acceleration by orders of magnitude. The result of this survey is consistent with the claim that the twelve goals described in the previous section (and surveyed above) reduce latency.

Measure	Definition	Best	Average	Worst	Surveys	Sessions	Period
Communication Latency	Time from request to reply	0.3 min.	**1.0 min.**	3.0 min.	24	9	3 years
Decision Latency	Time from request to decision	0.9 min.	**2.0 min.**	4.2 min.	34	10	3 years

Table 3: Summary of Latencies Observed in CIFE ICE Sessions The table provides averages from CIFE ICE participant surveys over three years that asked the best, average, and worst latencies observed during a just-completed ICE session. ICE at CIFE Consistently Produces Latency Measured in Minutes. At JPL's Team-X, we observed similarly fast transmission of requested information and requested decisions. Typical conceptual design practices have communication latency ranging from days to weeks, and decision latency is even longer. We believe latency often explains the long duration of traditional engineering conceptual design projects – including many losing up to $1M per day from delays – and that managing latency provides a method to improve collaborative efficiency.

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Project Quality Observed in ICE

Figure 3 shows results of surveys of project performance measures observed in ICE sessions at CIFE. The results support our claim that ICE sessions at CIFE perform well against the measures that determine a typical project success. Respondents generally felt the session was not "stressful," indicating a psychologically sustainable process, although we believe they found the sessions "exciting." Although one measure reflects poor performance – over fifty percent of respondents felt the session overran the schedule – practitioners are unlikely to reconsider ICE due to overruns of a few minutes because these projects last many months in traditional practice. Generally, participants found that the ICE method produced designs of acceptable quality, although there is room to improve in some areas. The observation that compressing schedule by orders of magnitude still produced designs of passable quality suggests that professionals can add more sessions or more time to bring quality up to, or beyond current standards while remaining far ahead of schedule. The results of this survey are consistent with the claim that reducing latency using the ICE targets can maintain acceptable product and process quality.

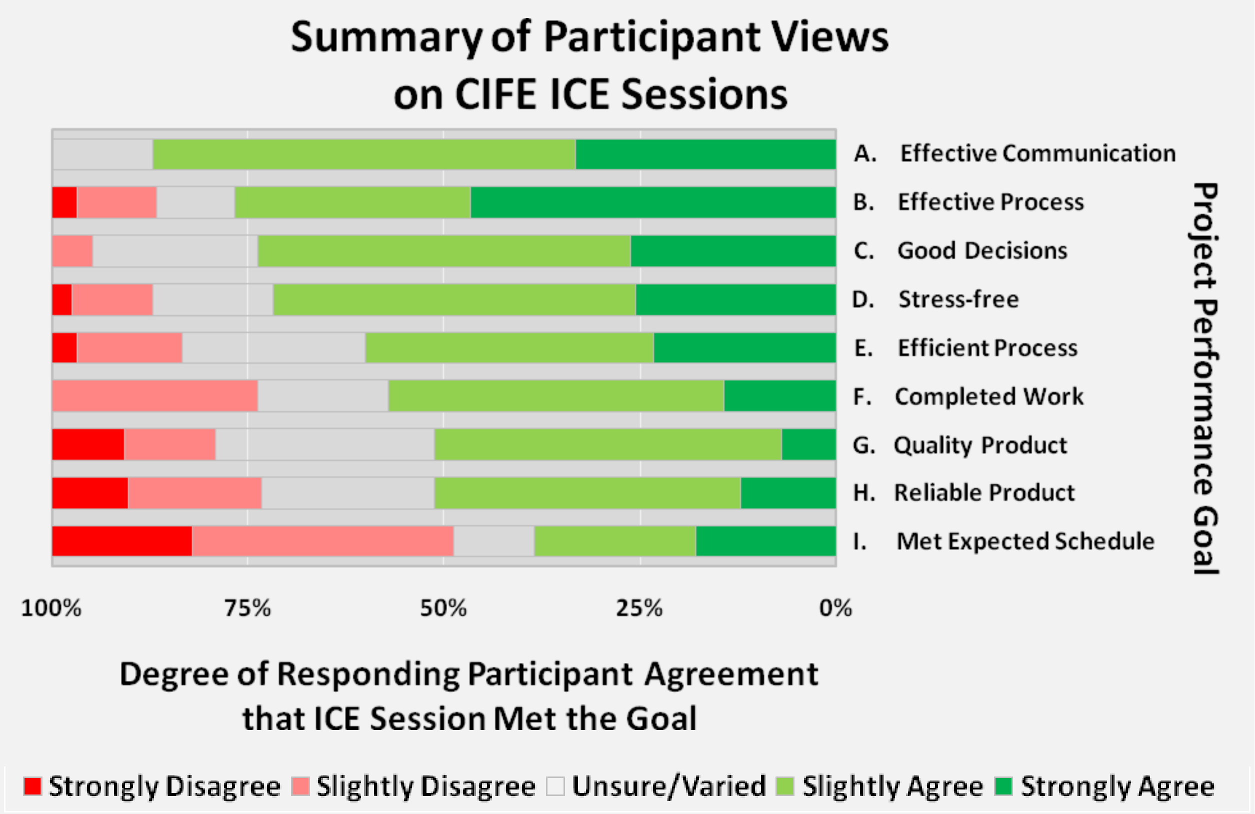

Figure 1: Summary of Quality Observed in CIFE ICE sessions. This figure charts the degree to which sessions supported measures of quality in the design process and designed product. Vastly accelerating project schedule and achieving low latency using the methods observed at Team-X might have sacrificed quality, however the results of this survey provide evidence the sessions developed a valid product using a sustainable process.

Conclusions

We view ICE as a "Just in Time" approach to knowledge work. Traditional collaborative engineering practices buffer design work between actors and endure frequent delays communicating. By contrast, ICE supplies multiple, simultaneous information flows with infinitesimal latency ("lead time") and high micro-scale reliability ("service level").

We offer coordination latency as a unifying, intuitive, descriptive performance metric, and we propose reducing it to near-zero as a project design goal. 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 the information or decisions that they need as soon as they need it allows the stations to move forward at a greatly accelerated, synchronized pace.

Existing literature does not fully explain how the extremes of parallelism, interdependence, and decentralization enable 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 that provides initial insights to begin answering this research question. Together with our observations of JPL's Team-X, our results provide evidence that organizations can repeat ICE success by managing the latency sources and subtask durations.

Discussion

A common intuition is that measuring and incrementally adjusting the enabling factors toward success conditions can substantially improve many projects' schedules, even without completely committing to ICE. However, ICE 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 suggest that organizational designers who seek to improve their collaboration effectiveness through latency reduction should attempt to co-align *all* of these factors within their specific organization.

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

ICE in Education

ICE sessions provide university researchers with a local source of rich, novel data and a way to field-test novel engineering methods easily. For example, CIFE researchers, seeing more clearly what the industry's standard tools do and do not provide, defined a multi-attribute, collaborative design, assessment, and decision integration method to serve in a role similar to the shared database at Team-X. The new method now serves in each ICE session and has spread to other courses and real projects [Haymaker and Chachere 2004, Haymaker et al. 2008]. The second half of this paper provides survey results on a range of ICE session behaviors.

Several times a year, the ICE course hosts industry sponsors who begin the session by presenting a real-world project design challenge. The students then conduct a three-hour ICE session culminating in a presentation of integrated models addressing the challenge. CIFE has also demonstrated ICE for large industry gatherings and hosted one-week training for engineers from industry wishing to learn the method.

ICE in Industry

Our successfully using ICE for building design, based on principles observed for space mission design, strongly suggests that ICE has great generality and potential in many segments of engineering practice. Our theoretical results suggest methods by which an important range of applications can adopt ICE in its entirety. Of equal importance, they articulate reasons why most organizations may find moving to ICE extremely challenging in the short term, and provide a focus of attention that can significantly improve their effectiveness in any kind of collaboration.

In our view, radical project acceleration through mechanisms like ICE presents both practitioners and theorists with an opportunity that is difficult to ignore. We draw attention to and shed light upon two principles of knowledge work. The first is that modern organizations supply four distinctive elements of a general rational framework: beliefs, alternatives, preferences, and procedures (or decision rules) [March 1994]. Knowledge-based exception handling particularly highlights the increasing dependence on, and interdependency among, the domain experts in our technical labor force. 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.

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, engineers possess clear alternative design choices that will be acceptable to their organizations, 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 latency-based analysis of ICE 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, productive changes may range from collocation to simply discussing patterns of delay among divisions. Technically, changes may range from measuring email response delays to setting 'core hours' when all workers are onsite.

From a theoretical standpoint, we also show why the Team-X 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.

It is reasonable to argue (based, for example, on evolutionary ecology theory [Hannan and Freeman 1989]) that if ICE performance were viable, the approach would be more widespread. The system perspective we present in the introduction suggests that this apparent conflict may result from a careful balance of factors that typically do not emerge in combination. For example, adopting a flat hierarchy with task parallelism, alone, might be disastrous in a traditional organization, even though they are complementary when combined with the other latency-reducing elements of ICE. Results from a computational experiment [as in Chachere et al 2004] might help assess the interactions of different combinations of enabling factors and suggest improvements relevant to both traditional and novel engineering methods.

Systems View

ICE is subject to the same forces as traditional design, but those forces have novel implications under its radical schedule compression. To convey this intuition, we describe ICE as analogous to operating a high-performance racecar. ICE engages the same considerations as standard design teams, but like the racecar, many elements of the total system are customized for high performance. The racecar has specialized engine, transmission, tires and even racetrack. Analogously, ICE requires expert selection and preparation for participants, the organization, the enabling modeling and visualization methods, and the design process the participants follow. Any bump in the track, hardly noticeable at twenty miles per hour, can be disastrous for a racecar at two hundred. Therefore, before a race, the track must be cleared and leveled thoroughly. Analogously, the Team-X “pre-session” structures the tasks, and chooses the participants and the variables of interest for the project at hand. During a race, a driver responds principally by reflex, in accordance with training and experience, because there is little time for deliberation. An operating ICE team also prevents failure by deciding quickly, conclusively, and well.

This “Systems View” suggests that an ICE implementation lacking any one critical adaptation may result in unimproved performance, or even in 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. ICE has many challenges and pitfalls. Even in domains where ICE is viable, organizations may fail to navigate them.

One view is that the racecar and ICE team have structural isomorphism with the standard car and design team because the fundamental requirements and solutions in play are the same. Even while operating at high speed (low latency), a racecar is still a car (multi-disciplinary design project), and we can understand it by understanding the behavior of the fundamental mechanisms in a car (project). From this view, it seems ICE has shown nothing more or less than that the right set of locally specialized, balanced adaptations to general design methods vastly alter performance.

Project design features that are irrelevant under some conditions, however, may become prominent in others. To continue our transportation analogy, at low speeds, wind resistance is typically unobserved and inconsequential, but at high speeds, wind resistance is apparent and motivates streamlining. Similarly, we have observed that ICE elevates communication response latency to a position of fundamental prominence in engineering.

Creative engineers revolutionized transportation by outfitting a vehicle with wings, transforming a newly identified enemy, wind resistance, into an ally, lift. We suggest that, analogously, creative engineering managers might learn to use latency to turn a principal engineering enemy, the design constraint, into an ally as well. Traditional engineering practice often consists of engineers making design decisions, referring them to other engineers, and then learning that dependent engineering disciplines include constraints that the proposal violates. In this common process, the likelihood of having wasted time is roughly proportional to the number of constraints, and the delay resulting from rework is proportional to the communications latency. Achieving zero latency minimizes the cost of communicating design choices that violate dependent engineering trade constraints.

Even a zero-latency team can waste time generating and comparing options eventually deemed invalid. To analyze this problem, we define "negative latency" to measure the phenomenon of an engineer becoming aware of a constraint *before* proposing a design decision that has the potential to violate that constraint. The notion of design team experience reflects this advance knowledge of dependencies on other trades' constraints. Constraints known in advance reduce the size of design trade space, which can simplify the original design task. Thus, the direct effect of having more constraints is to *increase* the duration of engineering work when latency is positive, but to *decrease* the duration when latency is negative. Experienced ICE teams, like Team-X, have learned to "fly" – to institutionalize reducing latency even into the negative range – and to literally thrive on solving hard problems.

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