The Integrated Concurrent Enterprise

By

David B. Stagney

B.S. Mechanical Engineering, Northwestern University, Evanston, IL 1999

Submitted to the Department of Aeronautics and Astronautics and the Sloan School of Management in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Aeronautics and Astronautics
and
Master of Science in Management

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Signature of Author……………………………………………………………………………
Department of Aeronautics and Astronautics
Sloan School of Management
August 13, 2003

Certified by……………………………………………………………………………………
Deborah J. Nightingale
Professor of the Practice, Department of Aeronautics & Astronautics
and Engineering Systems Division, Thesis Supervisor

Certified by……………………………………………………………………………………
Donald B. Rosenfield
Senior Lecturer of Management,
Director, Leaders for Manufacturing Program

Accepted by……………………………………………………………………………………
Edward M. Greitzer
H.N. Slater Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Accepted by……………………………………………………………………………………
Margaret Andrews
Executive Director of Masters Program
Sloan School of Management

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ABSTRACT

Organizations have traditionally battled the onslaught of complexity by decomposing problems into small pieces. Specialized workers then complete these tasks and integrate the results into a final deliverable. While this approach simplifies each particular task, it leads to bureaucratic, expensive management structures or sub-optimized system designs.

Within the context of large-scale projects, this thesis analyzes several of the current and emerging business processes that have been introduced in order to improve upon the decomposition method. Techniques such as QFD, DSM, IPPD, MDO, ICE and MATE-CON are analyzed by way of a three-dimensional Concurrent Engineering framework. An in-depth case study based on 15-months of work shows how the implementation of Integrated Concurrent Engineering (ICE) can dramatically improve the quality and speed of the design process, and can promote innovation and learning. Team metrics are presented and analyzed.

As measured theoretically and practically, no single approach discussed in the paper brings a satisfactory resolution to the challenges identified. The author argues that, despite their initial successes, even the case study team failed to strike a balance between the technology, people and process elements that must be systematically managed in order to create and sustain excellence in any complex undertaking. The structure of the team's corporation – the financial, organizational and human resource processes – have stalled the case study team just short of an enterprise-wide breakthrough.

Finally, the author argues that radical improvements in business productivity will not be achieved through the incremental improvements analyzed in the first chapters. Rather, the very nature of the corporation must be re-thought and re-born. Eliminating the trap of decomposition, the author presents a vision for the Integrated Concurrent Enterprise, or ICEnterprise, along with a concept of operations and detailed implementation guide.

Thesis Supervisors: Deborah J. Nightingale, Professor of the Practice, and Donald B. Rosenfield, Senior Lecturer

For Samantha.

My partner, my guide, my inspiration. I could not have done this without your tireless support and faithful reassurance. I can't wait for a wonderful life together.

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BIOGRAPHY

David Stagney will assume the title of Value Stream Improvement Leader at Moog, Inc (a worldwide manufacturer of precision control components and systems) in September of 2003. Moog's high-performance actuation products control military and commercial aircraft, satellites and space vehicles, launch vehicles, missiles and automated industrial machinery.

Prior to his graduate studies, Mr. Stagney was responsible for the production of cryogenic valves for launch vehicles, a role in which he successfully implemented a number of Lean Manufacturing techniques.

Mr. Stagney currently resides outside Buffalo, NY with his fiancé, Samantha Frank. He enjoys racing his Laser sailboat, cooking and socializing with friends.

For updated contact information, please refer to the Leaders for Manufacturing Program office via MIT (http://web.mit.edu), or contact david.stagney@sloan.mit.edu.

NOTE ON PROPRIETARY INFORMATION

The case study presented in Chapter 4 of this thesis is the result of a 15-month collaboration between the author, MIT's Leaders for Manufacturing Program, MIT's Lean Aerospace Initiative, and a large US aerospace corporation. In order to protect proprietary company information, the data presented have been scrubbed of all details that may reveal the name of the company that participated in the research. Factual content was not altered, however names and terminology were disguised. For numerical data, unit labels were removed and the numbers were normalized to protect competitive information.

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Chapter 3: Integrated Concurrent Engineering (ICE)– In Theory, A Dominant Approach

Chapter 3 will describe how the Integrated Concurrent Engineering Process (ICE) – if implemented effectively in tandem with the MATE process (Multi-Attribute Tradespace Exploration) – can strike an efficient balance between strong and weak systems engineering philosophies described in Section B above.

Chapter 4: ICE – In Practice, An Organizational Quagmire

Chapter 4 will explore the implementation of the ICE and MATE-CON processes through a detailed case study of the RTCE (Real Time Concurrent Engineering) Team. It will also raise the organizational implications that are uncovered when a project focuses too heavily on the technical issues – to the detriment of people and processes. The research presented in the case study was gathered over the course of more than a year of work with a team in industry that was struggling to radically redesign their product development process in the hopes of cutting costs, improving quality and building competitive advantages.

Chapter 5: The Integrated Concurrent Enterprise – Vision

After a review of the research findings, Chapter 5 will then lay out the author's vision for the Integrated Concurrent Enterprise – its guiding principles, structural and organizational attributes.

Chapter 6: The Integrated Concurrent Enterprise – Implementation

Chapter 6 contains a detailed implementation roadmap for building an Integrated Concurrent Enterprise. Whether transforming an existing company or building an ICEnterprise from the ground up, this guide will provide the necessary, courageous steps to create and lead a revolutionary new type of organization.

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Chapter 1: Managing Complexity – Sub-Optimization and Iteration in Product Development

Section 1-A: Introduction

During World War II the American Aviation Corporation signed a contract to deliver a new fighter aircraft – the prototype was due 120 days after the agreement was made. The resulting P-51 Mustang was designed in 102 days. The achievement harnessed about 600,000 hours of effort, and included some breakthrough technological advances that made it one of the decisive weapons of the air war (Conradie, 2001).

Sixty years later, modern corporations still confront the same challenges that the P-51 team faced – yet similar success stories are rare, and even more difficult to repeat consistently. In fact, more often than not, the news is populated with stories of huge product and process failures. What prevents groups of intelligent and motivated people from achieving breakthrough success? Why do organizations that were once described as 'fearless' or 'innovative' become bloated and bogged down in their own mediocrity? How can a new generation of leaders re-write the paradigms of business and project management in order to break the systemic death spiral of increasing cost and complexity?

Section 1-B: Complexity and the Decomposition Method

Humans have worked together to solve problems throughout history. As these problems have become more and more complicated, people have developed organizations that were highly efficient at breaking down complex problems in order to solve them. Unfortunately, this approach has meant that as the size and scope of each new project increases, so does the resulting cost, number of people, lead time and management difficulty.

Henry Ford first mastered the now-dominant approach to managing complexity: decomposition. Specialization of labor emerged in the factories near Detroit early in the 1900's as a way to reduce the total labor hours spent manufacturing Ford' Model-T car. By breaking the assembly of one automobile into a series of small, easily learned and quickly performed tasks, Ford could employ workers with little education and even less training. This revolution allowed him to reduce the total hours spent assembling each car from 700 to less than 100, but came at the expense of overall system knowledge. Individual assemblers changed from skilled craftsmen to interchangeable, robotic workers (Ydstie, 2003).

Although Ford and his engineers retained their overall knowledge of how their product worked, line employees lost their system-level perspective. Without an understanding of how a car worked, individuals had difficulty identifying problems. If they did see a problem, they were unable to fix it themselves. Innovation was stifled by the decomposed structure of the organization – breaking complex systems down into manageable sets of data, people, disciplines and organizations was straightforward; it was the re-composition of those diverging subsystems that served as the ultimate demise of many great projects (Belie, 2002).

Nearly a century later, a majority of today's high performance products and systems are designed and manufactured in much the same manner that Ford's Model T was. (For context, some examples of the systems that apply to this discussion are airplanes, spacecraft, ships, communication networks, transportation systems, skyscrapers, public works projects, and distribution systems. The costs of these projects can range from 100 Million Dollars to Tens of Billions of Dollars, and development times can range from two to 20 years.)

A number of powerful techniques have been applied in an attempt to improve the design and execution of the "knowledge assembly line." In general, though, many knowledge workers (engineers, designers and project managers) in modern corporations face a similar set of systemic barriers that Ford's workers did. They are highly successful at optimizing the small section of the system they are responsible for – but, without knowledge of other subsystems, or visibility to the trades being made, they are helpless to create innovative system solutions.

The technical problems faced early in the 20th century have become even more complex today –especially in the realm of new product development. The design and fabrication of advanced systems now requires engineers with dozens of unique specialties, often scattered geographically and organizationally. Large companies continue to acquire smaller ones in an effort to lower cost and increase strategic synergies even though the transitions create additional complexity and cost. In most cases, even when the big-picture fits together, at an operational level, research has shown that there is only a 10% probability that two employees who sit 10 meters apart will communicate with each other at least once a week (Browning, 1996).

To compound the issue of design complexity, the leaders of the product development teams find themselves in a competitive environment that has shifted from a seller's to a buyer's market. This trend requires an increasingly globalized approach and demands the rapid development and application of new technologies (Berndes and Stanke, 1996).

Managers have realized that re-creating some of the essential elements of the successful product development teams they studied – small size, strong leadership and a sense of urgency – were difficult to sustain from project to project. As customers demanded higher quality, prices dropped, technologies advanced, and markets globalized, it became impossible for any reasonably sized team to achieve similar results on a consistent basis (Prasad, 1996).

Problems with new product development projects often take on one of two forms:

1. The original design was highly organized but extremely sub-optimized (traditional robust, centralized systems engineering), or
2. Integrated high-performance designs were not flexible enough to deal with the inevitable changes that were brought out by political, economic or manufacturing realities (weak, ad-hoc systems engineering).

In the first scenario, a system is decomposed into rigidly defined subsystems with rigorously delineated interfaces. Large requirements documents are generated that allow each subsystem to be designed, tested and manufactured in nearly complete isolation. Final system integration is performed at the conclusion of many years of work, and problems that arise are often dealt with by the heroic application of labor and capital. The practice of this traditional, conservative approach has been reinforced by data from numerous expensive and embarrassing system failures (Newman, 2001), however it is costly and complicated to implement, and the lack of system-wide knowledge again prevents innovation and optimization.

As noted by Mosher, (1996), “with this approach there is no guarantee that a systems level focus will be taken, and the resulting design is usually a collection of high-performance subsystem implementations that when integrated are not a highly efficient system implementation.”

Despite these observations, there are still many proponents of the decomposition method. Most believe that the advances in information technology alone can overcome the barriers between subsystem designers in order to yield system optimizations (Garcelon, et al, 1999) and (Braun, et al, 1996). Others believe that new processes can help define the correct decomposition and integration structures (Browning, 2001). (Crawly and de Weck, 2001) describe the role of the “system architect” and a process for systems “architecting” that is based on the decomposition method:

> “An architect must be able to think holistically, and:
>
> - Define boundaries, and establish goals and functions,
> - Create the concept which maps function to physical/logical elements
> - Define decomposition, abstraction hierarchy and inter-element interfaces.
>
> An architect is not a generalist, but a specialist in simplifying complexity, resolving ambiguity, and focusing creativity.”

Alternatively, a different definition of systems engineering exists, where “…the focus is on the system as a whole rather than on the individual components of the system, as the individual components and subsystems do not necessarily need to be individually optimized for the system to perform optimally. Rather, optimal performance results from the synergistic integration of the components (Jilla, 2002).”

Using this ad-hoc approach, small teams such as the fabled “Skunk Works” of Lockheed Martin, have produced innovative designs rapidly and at a low cost.

However, these integrated, high-performance designs are often completed outside the traditional operations of the sponsoring company – this is acceptable for a small number of prototypes or advanced units, but significant time and resources must then be spent to alter the design so that it can be produced cost effectively in larger quantities.

On October 26, 2001, Lockheed Martin Corporation won a historic competition that pitted the best aircraft designers in the world in a battle of monumental proportions – the winning team would obtain a contract for the Joint Strike Fighter worth nearly 200 billion dollars over the next 20 or more years. The winning design included a number of innovative concepts and advanced technologies, but despite the technical challenges, both teams were able to successfully fly prototype designs as a part of the competition. The government paid a total of over one billion dollars for these prototype development programs. Yet another 26 billion dollars will have to be spent over the next 7 years before a production unit will ever take to the air (Preble, 2002). Vast sections of the design will be redone, and numerous compromises will be made in order to create a manufacturable fighter that meets the ever-evolving demands of its military and political customers.

The question that this situation presents is one that is the result of thousands of failed projects – "Do you want it now (i.e. a working prototype), or do you want it right (i.e. a production version that is safe and reliable)?" Each time new projects are undertaken, managers apply the latest technologies and business processes – they constantly re-think where, by whom and with what that work gets done in order to try to find a compromise between these two choices. This is almost the same as the "better, faster, cheaper" paradox that many in the aerospace industry have been battling against for the past few years. Can a radically different way of how people work together eliminate these choices altogether and free people to focus on innovations that reduce the complexity or their products without the associated organizational complexity?

Section 1-C: Sub-Optimized Designs - "The Point-Design Paradigm"

Diller (2001) identified a list of common process deficiencies that plague system designers:

- Establishing design requirements a priori with limited consideration of other options.
- Inadequate means of systematically evaluating broad trades in the early stages of design
- Lack of regard for the complete preferences of the decision maker.
- Inaccurate characterization of decision maker preferences.
- Pursuit of a detailed design without understanding the effects on the larger system.
- Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest.

The results of these faulty process steps were adapted by Browning (1996) from Sage (1992), and should be extremely familiar to any system designer:

- "Large systems are expensive.
- System capability is often less than promised and expected.
- System delivery is often quite late.
- Large-system cost overruns occur often.
- Large-system maintenance is complex and error prone.
- Large-system documentation is inappropriate and inadequate.
- Large systems often cannot be adapted to a new environment or modified to meet evolving needs.
- Large systems often do not meet reliability requirements.
- Large systems often have unanticipated failure modes.
- Large systems often do not perform according to specifications.
- System requirements often do not adequately capture user needs.
- Unanticipated risks and hazards often materialize.

- Large systems are often cumbersome to use, and system design for human interaction is generally lacking.
- Individual subsystems often cannot be integrated."
- The system is of low quality.

Of the six process deficiencies noted by Diller above, the first item stands as one of the most frustrating to system designers. Great systems engineers – especially ones with many years of experience (recently described as system "architects." (Crawley and de Weck, 2001)) – can often visualize a design solution in their head very early in the design process. This process is often the source of many of the great 'skunk-work'-type designs – one person's ideas translated into reality by a dedicated team who trusts the vision of their leader without question. It is often the case that the initial sketches of a concept are frozen very early in the product development process – the rest of the work centers around making that shape perform as needed, sometimes at great cost and delay.

For example:

> "...The conceptual space [systems] design process is very unstructured.... design researchers have found that actual design does not follow [an organized] process.... designers often pursue a single design concept, patching and repairing their original idea rather than generating new alternatives. Conceptual space [systems] design also suffers from this single design concept fixation.... these methods [of conceptual space systems design] explore a limited number of options with three to four being the limit due to schedule and cost constraints....[current] approaches tend to settle on a single point design very quickly. – (Mosher, 1998)"

Section 1-D: Sub-Optimized Organizations – "Over Budget. And Late. Again."

Besides increased complexity of technology, system designers have come up against another great reality in the last few decades: pure system performance is no longer the only measure of project success. There are other constraints that system designers must manage; budgets, schedules, personnel, sub-contractors and regulatory issues all influence the outcomes of large system designs. While most systems engineers have been promoted because of their past success with technical problems, few are trained adequately to deal with these new challenges, and even less have the authority to make changes to their organization in order to complete their projects in the most efficient manner.

For example, most systems engineers are assigned to a team of existing personnel instead of being able to choose their own team. They often have to compete with other high-profile projects for the time of talented individuals or particular functional departments. Since these leaders work in large corporations where others outside the project set their budgets, the funds that they do obtain are subjected to heavy “taxes” in the form of overhead rates that are often 200 to 300% of the actual expenses incurred. The project leaders therefore spend a great deal of their time managing their accounting “charge numbers” to avoid running over budget, and the cost of this is often lengthy delays in work that needs to be done early on in order to reduce risk later in the program.

Legacy systems are often employed – regardless of their applicability to the project at hand. Despite the efforts at standardization however, each project is managed very much according to the personality of the system engineer. Therefore, data that are created are usually not easily accessible or understood by other project teams.

These organizationally imposed complexities have had the most visible effects in the US defense industry. Between 1965 and 1994, the average development time for a major defense system increased over 80 percent – to an average of over 9.3 years to design and field each new system (Murman et al, 2002). During this period, “development times and costs grew with product and institutional complexity. Cost overruns were solved by stretching schedules to postpone outlays…consequent cost increases and related budget issues encouraged more government oversight, which reduced industry flexibility (Murman et al, 2002).”

Section 1-E: The Challenge

The competitive pressures on today’s product development teams are relentless, but organizations have responded by creating and applying new techniques in order to create innovations in rapid succession (Berndes and Stanke, 1996). Quality Function Deployment (QFD), Design Structure Matrix (DSM), Multidisciplinary Design Optimization (MDO), Integrated Product Teams (IPT's), Integrated Product and Process Development (IPPD), and Concurrent Engineering (CE) are some of the more popular processes that have been applied to the problem of managing highly complex design projects.

Each is, in its own rights, an elegant and powerful approach to combating the difficulties described above, but each is also susceptible to the fact that non-technical barriers such as those identified by (Belie, 2002) can limit the sustainable impacts any one process can have.

Regardless of the theoretical or axiomatic perfection any one process may contain, if it is not implemented wholeheartedly and in the proper context, the expected benefits will fail to materialize. The designers of complex systems must not only create systems that perform as specified, but must consider the organizational context in which they work. How do current and emerging design processes harness technology to become more efficient and produce higher quality output? How do organizational issues affect the people who do design work and the quality of the work they produce? How can project managers apply and adapt the most appropriate design process to each new challenge they face? The technology, people and process categories will form the basis for the analysis presented in the first four chapters of this thesis.

As these and other related questions are answered, a wide range of existing and emerging product design processes will be examined in depth. After the strengths and weaknesses of these processes are understood, and an in-depth case study is presented, a new organizational concept will be proposed: The Integrated Concurrent Enterprise (or ICEnterprise). This new organization will tackle the technical, people and process questions identified above and will pave the way to a sustainable new future for high-performance system design.

The remainder of the thesis is organized as follows:

Chapter 2 will present and analyze the most widely practiced product design processes. Each will be examined in the context of an analytic framework that helps to capture the full scope of the technical, people and process questions.

Chapter 3 will describe how the Integrated Concurrent Engineering Process (ICE) – if implemented effectively in tandem with the MATE process (Multi-Attribute Tradespace Exploration) - can strike an efficient balance between strong and weak systems engineering philosophies described in Section B above.

Chapter 4 will explore the implementation of the ICE and MATE-CON processes through a detailed case study and will raise the organizational implications that are uncovered when a project focuses too heavily on the technical issues – to the detriment of people and processes. The research presented in the case study was gathered over the course of more than a year of work with a team in industry that was struggling to radically redesign their product development process in the hopes of cutting costs, improving quality and building competitive advantages.

After a review of the research findings, Chapter 5 will then lay out the author's vision for the Integrated Concurrent Enterprise – its guiding principles, structural and organizational attributes.

Chapter 6 contains a detailed implementation roadmap for building an Integrated Concurrent Enterprise. Whether transforming an existing company or building an ICEnterprise from the ground up, this guide will provide the necessary, courageous steps to create and lead a revolutionary new type of organization.

Finally, Chapter 7 will summarize the findings of this thesis.

Chapter 2: Concurrent Engineering – A New Hope

In order to understand the proposed Integrated Concurrent Enterprise, and the Technology, People and Process issues that apply to all project implementations, it is important to understand the business processes that currently dominate the product design profession at many large engineering companies.

As the twentieth century progressed, and the pace of technological advancement accelerated at an unprecedented pace, organizations began to have problems with the traditional decomposition method. Functional specialties grew so large and segregated that inefficiencies based on poor communication, mistrust and redundancy began to surface along many organizational boundaries. Corporate and Academic leaders therefore proposed and implemented a number of business practices aimed at re-integrating people and information so that key tasks could be completed in a concurrent manner.

Section 2-A: History of Concurrent Engineering (CE)

The term "Concurrent Engineering" (or CE) refers to a number of integrative approaches to the product design and development process. The Institute for Defense Analysis offered a working definition of CE in 1988:

> "A systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developer, from the outset, to consider all elements of the product lifecycle from concept through disposal, including quality control, cost, scheduling and user requirements." (Source = society of concurrent product development web site: http://www.soce.org/ce/ce4.html)

The American Production and Inventory Control Society defines concurrent engineering as:

> "A concept that refers to the participation of all the functional areas of the firm in the product design activity." (Hall and Usher, 1999)

CE has also been referred to as "simultaneous engineering," "life-cycle engineering," "parallel engineering," "multi-disciplinary team approach," or "Integrated Product and Process Development (IPPD)." (Prasad, 1996)

The ultimate vision for CE is a system-level process that tackles head-on the issue of complexity in product design. By either re-arranging when work is done in an organization, or whom it is done by (adding cross-functional representatives), Concurrent Engineering Techniques aim to eliminate the decomposition and point-design paradigms identified in Chapter 1. Each applies a unique set of Technologies, People and Processes in the hope to produce innovative, high quality products more efficiently.

Despite the inherent imperfections in any CE implementation, the impacts that these new processes have had are dramatic and tangible. As reported by the National Institute of Standards & Technology, Thomas Group Inc., and Institute for Defense Analyses in Business Week, April 30, 1990, they "include 30% to 70% less development time, 65% to 90% fewer engineering changes, 20% to 90% less time to market, 200% to 600% higher quality, and 20% to 110% higher white collar productivity."

Section 2-B: PSI: A Framework for CE Analysis

Berndes and Stanke (1996) proposed a framework that concurrent engineering leaders could use to guide the development of their processes. Keeping in line with the spirit of CE, we should define a measure of performance in terms of product and process innovation as well as speed, flexibility, and completeness. Their three "guiding principles" form the basis for the analysis this chapter will propose. The degree to which each product design process displays a balance between parallelization, standardization and integration (or "PSI") can help predict the relative levels of performance each team will attain. Together, these principles incorporate the key subjects of the three questions posed at the end of Chapter 1 – *technology, people, and process*. The PSI criteria are therefore a comprehensive foundation for analyzing current processes and proposing a new organizational model.

Parallelization: The goal of the first concurrent engineering processes was to streamline the total amount of time spent on product development. Rather than the traditional, serial sequence of work, teams began to work in parallel, phasing their efforts so that tasks that were not immediately dependent upon each other could be completed simultaneously by different functional groups. This concept essentially led to an accelerated execution of linked processes – an approach that required a very detailed level of process knowledge and project management. Synchronizing the efforts of many sub-teams or individuals working in parallel is a difficult leadership challenge, but research has shown that through closer coordination, new product development teams will be more successful (Griffin, 1992).

Other research into teams has shown that a focus on "task processes" rather than just group "cohesiveness" is more indicative of team success – thus coordination and not simply proximity is essential to the effectiveness of any parallelization strategy (Ancona, 1992). Further, demographic diversity can lead to conflicts in a group, so effective team leadership, or coordination is absolutely necessary. However, excessive parallelization can create disproportionate levels of complexity, and each project should be planned with the appropriate scope, objectives, resources and experiences fresh in mind.

For the purposes of our analysis, we will provide two criteria that must be satisfied in order to state that any of our CE processes meet the goals of parallelization. Clearly, there are several underlying assumptions that the author supposes have been met if a process will be judged as having satisfactorily achieved the intent of each criterion. As an example, if an analysis is to be performed on a CE process at all, one can assume that it has at least attempted to fulfill the initial goals of CE (functional integration, innovation, speed, etc).

We can evaluate how well a product design methodology meets the goals of parallelization by the extent to which:

Independent processes are carried out simultaneously (PROCESS), and

> *Dependent processes receive information and attention just in time (PROCESS)*

Standardization: All organizations attempt to learn from past experiences and to create systems that enable people to become more productive over time. With efficiency as a first objective, and knowledge-transfer as a second, standardization efforts set out to design norms, routines and expectations that are codified and transferred throughout the organization. Successful CE projects must begin with explicit organizational structures, management and performance evaluation systems, training, and financing (Hall and Usher, 1999). Groups such as the Lean Aerospace Initiative at MIT have found that efficiency metrics should be set up with the goal of creating value (as defined by the customer) in complex systems rather than just "eliminating waste." This has been a typical generic objective that can lead to sub-optimal performance if undertaken without an appropriate focus on the end-user of a system (Murman, et al, 2001).

All complex undertakings need to have solid foundations that enable project participants to work with the confidence that they are providing essential inputs in response to accurate outputs from other team members. In order to avoid chaos, projects need to implement robust revision controls (Prasad, 1996), universally understood communication methods, appropriate definitions of interfaces and common organizational goals (Berndes and Stanke, 1996). Excessive standardization can create bureaucracy and remove individual and team accountability. The team should be granted time to adjust their processes based on the lessons learned during each subsequent iteration, and should set out to ensure that their process is adaptable enough to meet the project objectives without expending additional resources solely for the purpose of meeting the standard(s).

We can evaluate how well a product design methodology meets the goals of standardization by the extent to which it:

> *Systematically identifies and eliminates wasteful efforts based on a customer-defined value system (PEOPLE), and*

> *Enables the team to streamline knowledge-transfer both in real-time during a project and upon completion (TECHNOLOGY).*

Integration: Pulling together a cross-functional team – often across geographic and organizational borders – can be one of the most difficult aspects of any CE project. Functional diversity is a strong predictor of success for product development teams (Ancona, 1992). Further research has shown undeniable correlations between success and 'interfunctional harmony,' especially on projects that have had closely integrated marketing and R&D teams (Griffin, 1992). The necessity of integrating manufacturing, suppliers, customers and other partners has been proven just as important.

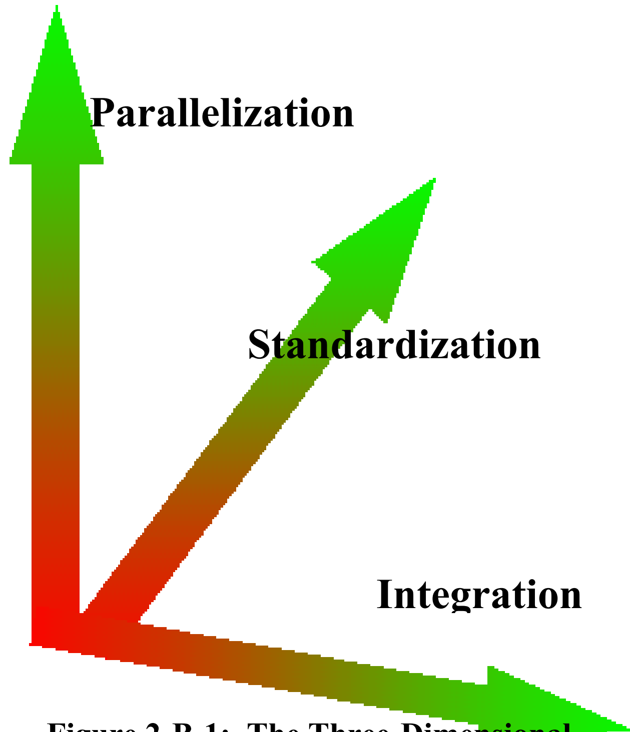


Figure 2-B-1: The Three-Dimensional PSI Concurrent Engineering Tradespace

More importantly, this guiding principle infers the need to integrate the disparate 'thought worlds' of all members of a cross-functional team (Dougherty, 1992). A high-performing team must share a common vision – a shift from functional thinking to system design – as well as the common structures and information included in the previous descriptions. This vision can be most effectively formulated and communicated by a senior manager who has key connections and respect throughout the enterprise and can thus unite the separate functional groups mentally as well as physically (Clark and Wheelwright, 1992). Studies have also shown that higher degrees of integration can yield more innovation than possible otherwise (Dougherty, 1992). Last, a note of caution. Excessive integration can lead to projects that last too long and involve too many people. Team sizes and operating processes should be chosen based on the objectives of each new project, not necessarily on the basis of past successes.

We can evaluate how well a product design methodology meets the goals of integration by the extent to which it:

Input and validation from the entire value chain (PEOPLE), and

To objectively explore the *full* *set of solutions (TECHNOLOGY)*

Framework Analysis: Figure 2-B-1 represents a three-dimensional concurrent engineering Tradespace. The three axes each measure the extent to which a proposed process meets the evaluation criteria given above for each of our guiding principles: parallelization, standardization, and integration.

Section 2-C: "Over-The-Wall" Engineering

This product development process is included only to establish a baseline from which our analysis can be performed, and is not an endorsed or standardized concurrent engineering practice – however many of today's corporations employ this work structure by default because of their large, segregated departmental organizations. For reference, this process has also been labeled as the "functional team structure" (Clark and Wheelwright, 1992). The term "Over-the-Wall" engineering refers to the information transfer events that occur in a serial development program (refer to Figure 2-C-1for the phases of a hypothetical program) where each subsequent department (marketing, design, manufacturing, etc) creates a design artifact representing all of thier work on a particular project. This artifact (a specification, report, set of drawings, etc) is then handed off to the next functional group. Typically, this process occurs in an organization in which the separate departments are isolated from each other by perceived walls that stifle communication and collaboration. Since these separate

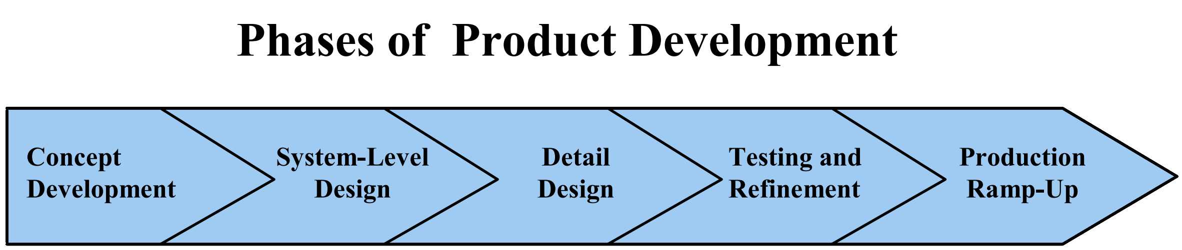


Figure 2-C-1: Sequential Phases of Product Development (From Ulrich & Eppinger, *Product Design and Development*, 1995)

groups often have very different cultures or "thought-worlds," the conclusions of one goup may appear incomplete or incorrect to another (Dougherty, 1992). This can lead to process inefficiencies or worse – departments blaming each other for product design failures.

Blinded by the inability to see past functional barriers, engineers or managers are unable to see opportunites for innovation – even if they were to propose these ideas, the structure of the process would prevent their implementation because other departments would not have the ability to understand the potential savings, nor would they be incentivised to take a risk on something that did not directly influence the performance of their functional group.

Another drawback of the "over the wall" team structure is the inevitability of rework. Complex designs, particularly in the aerospace world, do not often converge to a final solution on the first pass through each of the functional departments (Hulme, et al 2000). As design paramters change, work must be passed back to other departments so it can be redone or rechecked. This scenario is one of the most common causes of project delays and cost overruns.

NOTE: In the PSI Analysis Tables presented below, each Concurrent Engineering Process is evaluated as to the extent that it satisfies each of the PSI criteria. These evaluations were written by the author and are based on research and experience, however many alternative conclusions could be drawn from the same data. A ☑ *signifies that the author believes a particular item is satisfied, while an* ☒ *signifies that the author has noted a deficiency in that area. Each evaluation is followed by an explanation in the column below the evaluation.*

Analysis of "Over-the-Wall" Engineering					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
X	X	X	X	X	X
Process Flow is Serial.	Design Artifact created by each department and transferred only once per milestone.	Since departments work in isolation, potential product or process improvements are difficult to identify or implement.	During each phase of a project, functional team members communicate with each other via traditional means. Upon transfer from one department to another, a formal document (spec. etc) is created, and a meeting or presentation is held.	Each department adds their input in sequence as they complete their work.	One point design is chosen early in the process and modified incrementally throughout the lifecycle.

Section 2-D: QFD and DSM

The Quality Function Deployment, or "House-of-Quality" approach to product development originated in 1972 at Mitsubishi's Kobe shipyard in Japan (Prasad, 1996). QFD is a systematic, team-based approach that links specific design attributes with the needs of the customer. The process revolves around the creation of a large matrix that is used to rank the value that each design attribute adds to the overall product. The matrix tool also serves as a means of facilitating objective – rather than subjective – decision-making, acts as a repository of team knowledge and serves as a springboard for continuous improvement ideas (Prasad, 1996).

Research has shown that:

> "QFD appears to encourage the team to become more integrated and cooperative, but perhaps more inward looking. There is more communication within the team, even when the team crosses corporate boundaries. Furthermore, the team seems to be more self sufficient, solving their problems through horizontal communication rather than through management or by seeking information within the organization but outside the team. Most importantly, this new pattern of communication appears to increase team communication on all nonadministrative aspects of new product development." (Griffin, 1992)

Since QFD is such an intensively artifact-based approach, teams tend to close in and work in very tight groups that become separated from the rest of the organization after their initial research phases. This "seige-mentality" can lead to communication problems later on – colleagues who were not part of the original effort may have a hard time understanding or accepting the results of the analysis because they are not able to see the underlying assumptions or data in the high-level matrix that are the end-product of the team's work (Griffin, 1992). In addition, the opportunites for innovation in such a process are hindered from two directions. QFD seeks to assemble a product architecture by summing desireable and value-added attributes – this approach lends itself to taking the best of what was already done, and continuously improving it for each new application. It would be very difficult to propose and analyze a set of radically new solutions in this sort of system. However, even if the QFD team does propose an innovative new design architecture, they may encounter obstacles when they try to convince the rest of the organization that their analysis is correct. The lack of buy-in that may result would most certainly doom the innovative idea to obscurity while a new team is assigned to re-do the analysis.

Although QFD goes further down the quantitative path than the previous method discussed, and even goes so far as to seek out explicit interrelationships between determinate variables, it does so at the expense of flexibility and adaptability. The QFD process and subsequent analysis are very labor intensive and once completed, not something that are typically updated on a continual basis. Due to its complex structure, it is difficult to understand the impact of potential trade-offs or to perform sensitivity analyses. These techniques have been explored in the literature (Li-Pheng and Nai-Choon, 1999), but have not been widely implemented because they are typically beyond the scope or capability of most QFD teams.

Analysis of QFD Engineering					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
✗	✗	✓	✗	✓	✗
The conceptual design process is optimized, and includes input from many stakeholders, but traditional operations like detail design and manufacturing process design are left for subsequent teams.	Although the QFD artifact contains a significant amount of information it is a static document and not easily updated. Trade-offs cannot be evaluated easily once the matrix is complete.	Begins with a detailed analysis of customer needs and seeks to add new design attributes and processes only so far as they increase percieved customer value.	The process does create a substantial design artifact, however the introverted behaviour of many QFD teams combined with the complex matrix does not bode well for re-application of the knowledge they create.	QFD processes employ cross-functional teams that specifically seek out the preferences of their customers.	QFD does not allow dynamic re-evaluations or sensitivity analysis. Further, it builds the eventual design solution piecewise, avoiding the opportunity for radical innovations to be proposed.

The Design Structure Matrix methodology "provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems." (Browning, 2001) The heart of the DSM process, as with QFD, is a large matrix. The DSM matrix consists of a set of process tasks that have been identified as necessary to complete a proposed project. The list of tasks is placed both in the rows and columns of the matrix, and markers are then placed within the blocks that represent the intersection between dependent process tasks. An algorithm can then be run to re-order the tasks such that an optimal process flow can be identified. A very detailed description of the DSM process can be found at: http://web.mit.edu/dsm/Tutorial/tutorial.htm.

Recently, DSM analysis has been applied to an array of different processes: product development, project planning, project management, systems engineering, and organization design in order to reduce cost and risk (Browning and Eppinger, 2002).

Analysis of DSM Engineering					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
✓	✓	✗	✗	✓	✗
The goal of DSM is to identify couplings between process tasks. By re-ordering tasks to include planned iteration loops and opportunites for parallel processing, the method seeks to save project time and cost.	Although DSM is excellent at identifying dependent tasks, the process has no bearing on the actual execution of tasks, or the sytems created to share information. However, identifying the steps that must be completed prior to any task is very valuable.	DSM seeks to optimize the order that tasks are completed. Although this process efficiency leads to lower cost and shorter schedules, these attributes may not be the most important ones to a particular customer.	Once again, DSM is excellent at identifying dependent tasks, but the process has no bearing on the actual execution of tasks, or the sytems created to share information.	DSM helps to systematically identify all of the key tasks that occur during a given project, who does them, and what information is required or provided by each task. Integration is achieved by creating a visual table that represents and optimizes the interactions of all subsytems.	Even though DSM works with process tasks, not the specific product design ideas, these process tasks must be identified in the very first step of the DSM process, and are then optimized. Once the order is established, managers will be reluctant to deviate from their first point design, even if it is encountering difficulty.

Section 2-E: IPT's and IPPD

Integrated Product and Process Development (IPPD) has been heavily promoted by the Department of Defense. DoD Directive 5000.1 defines the process as follows:

> "A management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing, and supportability processes. IPPD facilitates meeting cost and performance objectives from product concept through production, including fielding support." From: http://dod5000.dau.mil/TERMS/index.htm

An Integrated Product (or Process) Team (IPT), is the multidisciplinary team chartered to use the IPPD process to design a new product and / or its associated life-cycle processes. It should be noted here that numerous companies employ IPT's without explicitly calling them such – they may refer to their efforts simply as "Concurrent Engineering" (or CE) – however the general approach (and corresponding result) is essentially the same.

The effectiveness of IPT's – specifically important gains made by integrating suppliers as key team members at an early stage – has been shown in a variety of case studies and research (Eisenhart, 1998). During the devlopment of the F-22 Raptor in the early 1980's, IPT's were used as the primary tactic for pulling together the technologies, capabilities and creativity of over 1,200 suppliers. The program was extremely successful in implementing many new technologies while meeting its affordability targets as a result of this approach (Muman, et. al, 2002).

On a large, complex project, a company may deploy tens or hundreds of IPTs to tackle very specific problems or issues. It is not unusual for employees who are considered experts to sit on multiple teams simultaneously, or for other team members to have a number of other projects also in process at any given time. Aside from these battles for employee prioritization and meeting time, these teams do not often take on the most efficient structres, and their leaders are not always the most experienced or influential people in the company. Since each new effort is a unique and separate process, there is little room for "process-improvement" activities because the circumstances of each effort are so different. Thus, the quality and cost of the output of each IPT can vary widely depending on the team makeup and, especially, the leadership (Wall, et al, 1999). Regarding team strucutre, even the Society of Concurrent Engineering states that "there is no checklist for implementing IPD because there is no one solution...each application will be unique." (Source: http://www.soce.org) Regarding the team leadership, research has shown how cross-functional teams that do not employ leaders with organizational clout, or "heavyweight" leaders, are not as effective as teams who do (Clark and Wheelwright, 1992).

Coordination and information sharing within and among the IPTs can also become a complex and inefficient process in itself. In 1995, a survey of IPT's in the aerospace industry noted that the ideal IPT team size "would be close to ten people" yet they found an average team had 40 members (only 26 of which were full time). The same study identified teams as large as 182 people (Klein and Susman, 1995). (Browning, 1996) has a lengthy discussion on the increasing complexity of interfaces within large teams and between large teams working on the same project. These structural challenges can increase the cost and duration of large IPT projects. In practice, the process of decomposing a large project into small, manageable tasks – the problem that IPT's were intended to solve – can be recreated. Although the tasks themsleves are no longer associated with one particular functional department, the separation between various IPT's can basically mirror the functional department boundaries that existed in the previous structure.

(Browning, 1996) proposed a number or "Integrative Mechanisms" (IM's) to address this particular issue and improve information flow. The key findings of his research were as follows:

- "The organizational structure of IPT's should mirror the product architecture as closely as possible.
- Since this is not completely possible, a systematic methodology should be used to group the IPT's and functional groups into system teams and to determine how integration will occur within these levels.
- Training should include team- and program-building components, which are best experienced by the IPT members together.

- Co-location is an excellent IM, although many do not utilize it in its most effective form. Constraints on co-location force the use of alternative IM's.
- Using heavyweight product managers (HPM's) effectively in large, complex, a high-risk development program is extremely challenging.
- Liaison roles are good IM's if they are placed at appropriate interfaces and made aware of their particular goals and responsibilities.
- Integration teams can provide useful interface mediation and cross-team integration, but they must have clear delineations of responsibility and authority and need not be composed entirely of managers.
- Interface contracts and scorecards are excellent ways of explicitly defining and monitoring interfaces."

Traditional Concurrent Engineering Projects, such as those typically undertaken by IPTs, not only leverage cross functional teams, but attempt to compress the serial nature of past methodologies. This approach, however, is often characterized by a heavy emphasis on up front planning and assumes that the development path is going to be certain (Eisenhart, 1998). The frantic time pressures that can be induced by parallel processing can stifle innovation from the beginning. Since peer groups are waiting for information from each other, the incentive for one group to take a risk on an innovative new idea is not high – under pressure, teams tend to revert to well-known and time-tested solutions.

Finally, IPT and Concurrent Engineering processes too often focus on the accomplishment of certain specific tasks, not on flows of information and trade-offs based on customer values. This can lead many teams to focus their effort too narrowly or to miss the opportunites for significant product or process innovations.

Analysis of Traditional Concurrent Engineering, or IPPD Engineering					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
✓	✗	✗	✗	✓	✗
Rather than working in series and in isolaiton within their home departments, all of the cross-functional IPT members meet and work together throughout the lifecycle of the project.	The operating structure of IPTs are usually not formalized enough to promote efficient data transfer. Most analyses are performed statically (data collected, a decision is made, and the team moves on) in sub-teams.	By uniting previously isolated co-workers, IPT's enable team members to have a system-level view of key processes, and therefore unique opportunities to improve business processes. However, work may not be performed with the goal of enhancing customer value.	Most IPT's function relatively informally or without "heavyweight" leadership. Most team knowledge is not codified for future use – once the team disbands, it is often difficult for other teams to learn from what was done (Browning, 1996).	Multi-disciplinary demographics of IPTs are usually representative of most key stakeholders in the value chain, especially key suppliers.	IPTs typically weigh the pros and cons of various options based on the inputs of various team members and stakeholders – a process referred to as "point-designing." Their structures are not set up to specifically explore a wide range of solutions in a dynamic fashion.

Section 2-F: MDO

In 1991, an AIAA Technical Committee issued a highly influential white paper. This document detailed the "State of the Art" of the emerging Multidisciplinary Design Optimization (MDO) Process. It described how a:

> "Designer can exploit the synergism of the interdisciplinary couplings provided that effective mathematical tools and methodologies are available. Thus, the

> Multidisciplinary Design Optimization (MDO) methodology that combines analyses and optimizations in the individual disciplines with those of the entire system is a technology that enables extension of the CE concept to the Design Phase (AIAA, 1991)."

Since that initial vision was published, the MDO process has evolved tremendously and has been applied to a vast array of complex system design projects. The fundamental concept of Multidisciplinary Design Optimization is to seek out analytical "solutions" to a given design challenge. Various computer models are integrated together in a structure that allows a higher-level program to run through hundreds or thousands of different design options. The goal of the analysis is to converge upon a solution that meets the objective function of the analysis while simultaneously satisfying a number of pre-defined constraints (Jilla, 2002).

Within the MDO research world, two competing philosophies have emerged. One believes that large MDO programs can automate the design process and locate solutions that are superior to those done by groups of designers – i.e. the "best answer" (Rohl, et al, 1998) – while the other believes that MDO programs exist to allow a small group of designers to do the work of tens or hundreds.

In the first camp are well-intended researchers who have followed their "infatuation with technology" (Neff and Presley, 2000) down a seemingly logical path, but have not necessarily examined the people and process issues that are associated with their design solutions. The technical results have been significant – despite the time and expense of writing large, complex software programs for each new design, the resulting solutions are often very efficient and address problems that engineers had been battling for decades. The creators of such programs however, reveal in their own words the philosophies they have subscribed to:

> "We have constructed an integrated design and analysis system which automates the early design phase of vehicle development." (Fenyes, et al, 2002)

> "The organization complexity of MDO is reduced by the sub-optimization problem. Further, by dividing the MDO problem into a multi-level optimization problem, transferring data from one discipline to another is simplified. It is shown that gradient based optimization can be computationally efficient." (Garcelon, et al, 1999)

> "Through subspace optimization, each group is given control over its own set of local design variables and is charged with satisfying its own domain-specific constraints. Communication requirements are minimal since knowledge of the other groups' constraints or design variables is not required." (Braun, et al, 1996)

On the other end of the philosophical spectrum, Jilla (2002) proposes an MDO approach that is intended to be more of a facilitation tool than a source for final answers. This approach works "by enabling a greater, more efficient exploration of the system trade space to find robust and perhaps even counterintuitive design architectures for further analysis that might not otherwise be considered." (Jilla, 2002)

For context, Jilla (2002) also complied a list of some MDO software tools created and used by various organizations:

Tool Name	**Organization**	**Description**
COBRA	The Aerospace Corporation	Automated assessment of program cost risk and schedule risk as a function of spacecraft complexity for interplanetary missions.
Concurrent Engineering Methodology (CEM)	The Aerospace Corporation	Mapping of "what if" cost and performance trade studies for Air Force missions.
ESSAM	Univ. of Colorado	Small Satellite bus component selection.
GENSAT	Computational Technologies	Object-oriented software that interconnects existing commercial satellite subsystem tools (STK, CAD, IDEAS, etc.) and component databases for space systems design.
MERIT	The Aerospace Corporation	Automated assessment of the cost and performance implications of inserting existing vs. new technologies into a spacecraft bus.
MIDAS	NASA Jet Propulsion Laboratory (JPL)	Analysis of proposed spacecraft designs via integrated tool executions on distributed machines.
Modelsat	ROUTES	Cost and mass modeling for communications satellites.
Project Trades Model (PTM)	JPL	Cost and performance prediction of novel interplanetary and space science missions.
QUICK	JPL	Spacecraft design programming language with extensive component databases and scaling relationships for conceptual spacecraft design.
SCOUT	The Aerospace Corporation	Single spacecraft mission bus component and launch vehicle selection.

Tool Name	**Organization**	**Description**
SMALLSAT	NASA Langley Research Center	Earth observation spacecraft sensor and satellite bus configuration.
SMAD	KB Sciences	Software automation of the calculations in Larson and Wertz's Space Mission Analysis and Design
SpaSat	Ball Aerospace	A preliminary spacecraft sizing, cost estimating, and orbital analysis tool for Ball Aerospace missions.

Analysis of Multidisciplinary Design Optimization (MDO)					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the <u>full</u> set of solutions? (TECHNOLOGY)*
✓	✗	✗	✗	✗	✓
The MDO technique uses computer models representing various functional disciplines to solve complex problems simultaneously.	MDO models take significant resources and time to create. Even though they integrate various disciplines, they do not produce an entire product design. Thus downstream, detailed designers must treat the output of an MDO as a rigid input to their work.	Although the optimization constraints of an MDO analysis may be important to a customer, the process itself has no impact on the way that other tasks in the project are completed.	MDO does create a design program that could potentially be used on another project, however they are usually so customized and complex that it may be easier for a new program to start over and create their own MDO.	Most MDO programs incorporate input from only a handful of disciplines because the complexities of creating comprehensive, quantitative models of every discipline within an organization are too great.	The strength of MDO programs are their abilities efficiently to generate and evaluate hundreds of thousands of design architectures.

Chapter 3: Integrated Concurrent Engineering – In Theory, A Dominant Approach

Quality Function Deployment, Design Structure Matrix, Integrated Product and Process Development, and Multidisciplinary Design Optimization are all Concurrent Engineering techniques that have proven successful in many cases but have theoretical or practical drawbacks as measured by the PSI criteria. As explained in the following chapter, Integrated Concurrent Engineering (ICE), enhanced by the Multi-Attribute Tradespace Exploration process (MATE) satisfies the theoretical measures, but may be very complex and expensive to implement.

Section 3-A: History of ICE

In 1994, a team at JPL's Product Design Center began to take advantage of the software and computational power that PC's had made readily available (Sercel and Wall, 1998). Their idea was not new (to enable true real-time concurrent engineering), but their approach was truly innovative: actually DOING their work together – not meeting, then doing work individually, then meeting again to compare answers and check for inconsistencies (Refer to Figure 3-A-1).

In the traditional approach, the time between meetings and individual or small group work (represented by the black arrows) is non-value-added. Due to the fact that designers are not always sharing the most current information, these design iterations must be repeated more times than necessary. A poll of managers from Lean Aerospace Initiative Industry Partners at MIT found that up to 40% of time spent in Product Development could be classified as "pure waste," while an additional 29% was felt to be "necessary waste." Further, the poll revealed that 62% of all Product Development tasks were idle at any given time (McManus, 2002).

System Engineers had long utilized the "bull-pen" work style to tackle the design of large, complex systems. Although many had attempted to re-create the fabled Skunk-Works success stories, as product and technology complexities grew it became impossible for any reasonably sized team to achieve similar results on a consistent basis. The new real-time concurrent engineering approach required a completely

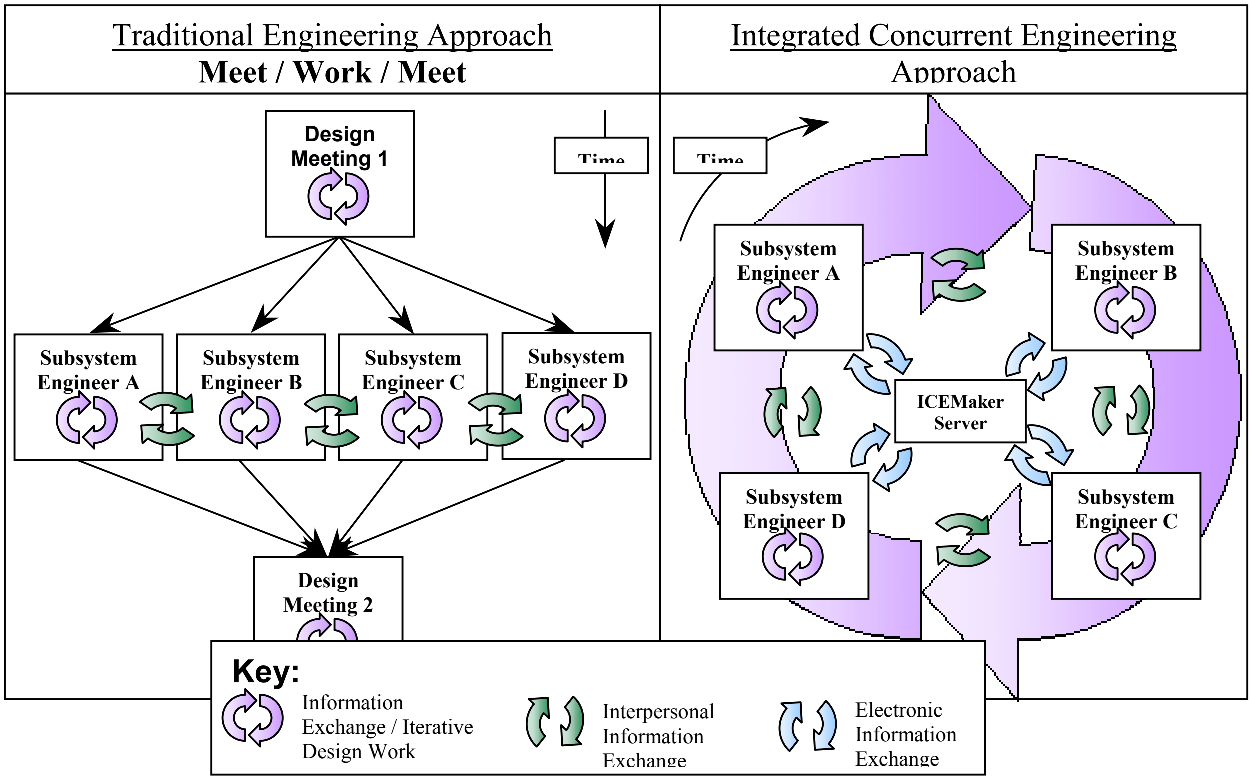


Figure 3-A-1: Comparison of Information Processing Paths between Traditional and Integrated Concurrent Engineering Philosophies – Meet / Work / Meet vs. Meet and Work

different work environment, new expectations and norms, a willingness to make mistakes rapidly and learn together, and an altogether new leadership approach.

The JPL team began to combine very simple software links with the concept of a highly trained, standing design team. With inputs from academia, the successful "Team X" evolved. This cross-disciplinary team employed powerful software analysis tools in a concurrent environment and an unprecedented pace. Working together in a specially designed room, the team took on three-week preliminary design / exploration projects (at a pace of about 50 per year).

A typical ICE team is composed of 5 to 20 members who each represent specific functional areas by operating their respective client spreadsheets. Each spreadsheet is built by a team member or functional group as an analytic tool that can output specific design information based on inputs from other clients (via the ICEMaker© database).

Physically, a typical ICE team is based in a homeroom that is approximately 25' by 25' (Refer to Figure 3-A-2 for a general layout of an ICE homeroom, and Figure 3-A-3 for a picture of a fully-functioning ICE design room). Individual clients are located around the periphery of the room, large projection screens are located at the head of the room, and the lead systems engineer and any customer representatives use a central table. Periodically, the team will come together and each designer will project a summary sheet of their work in front of the entire group for discussion – all other computer monitors are switched off so that attention is focused on each subsystem in turn. These "around-the-room" exercises allow each team member to understand the particular challenges their peers are facing, ensure that everyone is working from a common set of assumptions and provide a unique problem-solving forum.

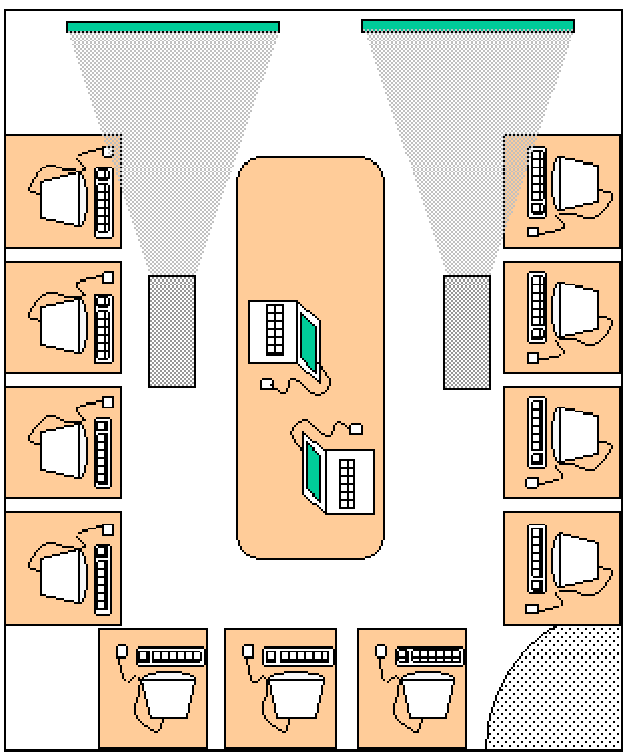


Figure 3-A-2: Schematic Layout of a typical Integrated Concurrent Engineering Homeroom

The initial results at JPL were dramatic; not only were average project costs slashed by over 80%, but the quality and speed of the work increased significantly. At last report, JPL had noted a 92% reduction in design time and a 66% reduction in cost using this method. (Neff and Presley, 2000).

Changes Noted to the Conceptual Design Process (Wall, et al, 1999)

From:	**To:**
Performance-Driven Design	Cost-Driven Design
Sequential Design	Concurrent Design
Hierarchical Process	Consensus Process
Deferred Problem Resolution	Real-Time Problem Resolution
Paper Data Exchange	Electronic Data Exchange
Stand-Alone Tools	Integrated Tools
Limited Design-Space Exploration	Comprehensive Design-Space Exploration
Zero-width Interfaces	Zones of Interaction
Requirements-Driven Approach	Hardware (Capabilities)-Driven Approach
Subsystem Engineering Models	System Engineering Models

From this point on, several other groups began exploring the processes that enabled real-time concurrent engineering. Aerospace companies began experimenting with such teams. Research groups at Caltech, MIT and Stanford obtained funding from the Air Force and NRO to study these processes through traditional research and exploratory classes. In addition, several consulting and software companies started up to link the theoretical and practical applications.

Integrated Concurrent Engineering (ICE) as currently practiced combines an integrative information system with a highly refined team process. As noted by one of the early pioneers in ICE, "when establishing a collaborative design team, it is a mistake to focus on information systems independent of the people who build, maintain and upgrade the systems… Unless a team has ownership and adequate coaching, elaborate computer models will die of neglect" (Neff and Presley, 2000).

Figure 3-A-3: Photograph of a fully-functioning ICE design room

The information exchange portion of ICE is made possible by the use of the ICEMaker© Software developed at Caltech (Parkin, et al, 2003), CO®, developed by Oculus Technologies, or similar PC-based information-exchange programs. ICEMaker© is an Excel-based tool that creates a central design database which can be accessed by every team member. Each design parameter stored in the database is published by one of the clients but can be read by any other client through a subscription process that refreshes the data regularly.

The power of this simple tool is immediately apparent. Even in concurrent engineering processes – where large-scale tasks were being performed in parallel – subsystem engineers would often have to wait at least a day and often up to a week for a design review meeting. Using this method, they would now have instant access to the latest design parameters being output by their colleagues. Using ICE techniques, the effects of even very minor design decisions are instantly visible to the entire design team. Therefore, effort is focused on creating a system solution rather than on working individually to design the best subsystem based on the information passed out at the last design meeting.

United Technologies Research Center

NASA's Jet Propulsion Laboratory – Team X

Boeing Satellite Systems, Inc. – CIEL

NASA Glenn Research Center – Design Center

California State University, Northridge – Design, Analysis & Simulation Laboratory

Figure 3-A-4: Current ICEMaker© Users (source: SpreadsheetWorld website)

The application of ICE techniques has led to significant innovations due to the reasons stated above. As one practitioner stated: "People are freed up to do what they do best: create innovate, exercise judgment, and communicate. The result is better designs with less time and money." (Neff and Presley, 2000)

However, the degree to which a team will propose and pursue an innovative new design architecture during and ICE session is solely dependent on the session leader, and the process employed. In this highly choreographed environment, individual team members do not have the power or time to explore potentially unique and valuable new ideas unless the session leader gives the entire team the time to do so. Most program managers are so enamored by the speed and efficiency with which they can create new designs using ICE that they lose sight of the opportunities to explore innovative new options – even though they would still be able to complete the total effort in far less time than they were able to using previous techniques.

Section 3-B: MATE-CON: A Guiding Light for ICE

Over the last two years, a group of researchers at the Space Systems Policy and Architecture Research Consortium (SSPARC, a joint venture of MIT, Stanford, Caltech and the Naval War College, funded by the NRO) have developed a unique facilitation process that substantially enhances the effectiveness of an ICE design session. MATE or Multi-Attribute Tradespace Exploration is a group process that is rigorously founded in economics and decision-making theory (Diller, 2002). The term "MATE-CON" refers to the addition of the MATE process to a conventional ICE, or Integrated CONcurrent Engineering design lab.

The basis of the MATE process is the ability to objectively evaluate an entire range of design possibilities on one scale – essentially trying to solve the age-old question of "how to compare apples to oranges." When a group of engineers sits down to design a complicated system, they often have to make choices between very different options. Each will have positive and negative characteristics that may not be directly comparable.

A brief example will help clarify how MATE-CON works. A traveler has many options when trying to decide how to reach a desired destination – one could fly, take a train, drive or perhaps take a boat. Within each of these potential modes, there are different options – public or private vehicles, for example. Most travelers decide upon a mode of transportation based on the total time they have available for the trip and the maximum amount of money they want to spend on the trip. Others have different factors that influence their decision. These could include a fear of flying, a desire for privacy, or a need to have last-minute flexibility. Although most people can intuitively trade off the pluses and minuses of various types of trips, they still need to have access to accurate information about each of the potential trips as well as a set of personal preferences. A MATE-CON process could therefore help a person decide how to make a particular trip by presenting a number of different travel options and ranking them according to a set of individual priorities.

For designers of complex systems – especially ones that may not have ever been built before – this ability to see a wide variety of design options all ranked according to the same criteria would be an invaluable asset.

The output of a MATE exercise is the *Tradespace* (Refer to Figure 3-B-1). This is a visual representation of all feasible mission or product *architectures* (ranked on the y-axis according to their effectiveness at meeting certain decision-maker defined performance *attributes*). On the other axis, they are ranked against their vehicle or lifecycle *cost*.

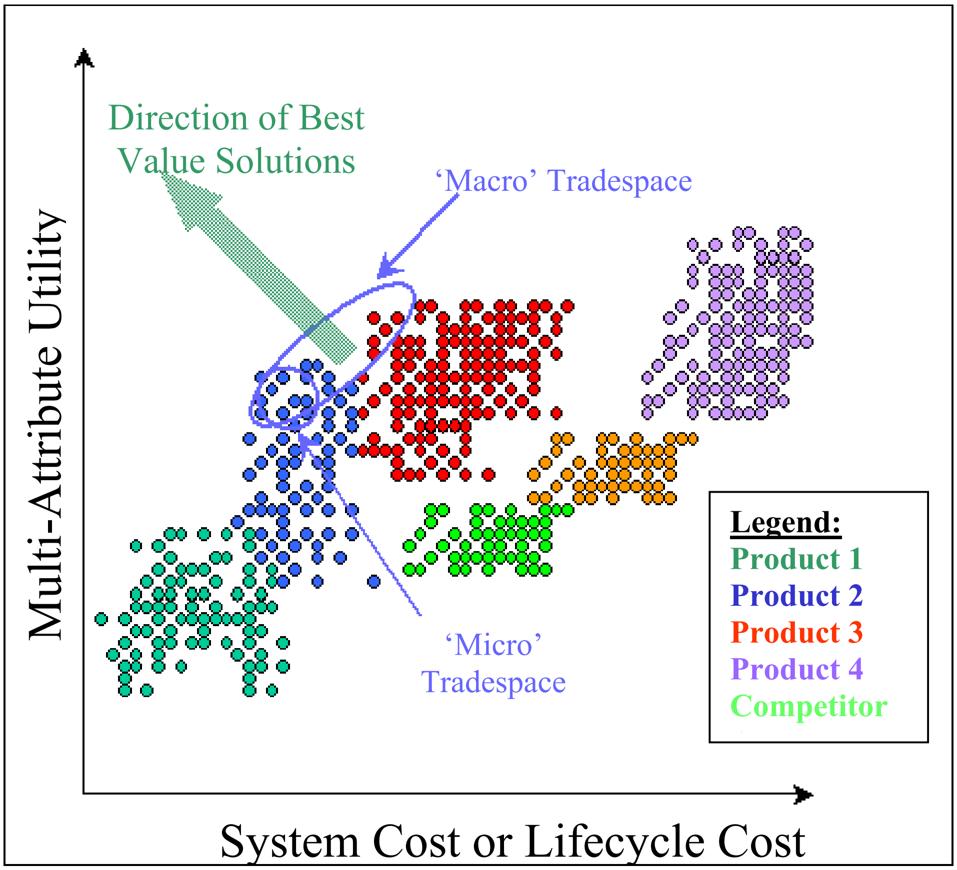


Figure 3-B-1: Notional Multi-Attribute Tradespace (Sample output of a MATE-CON Process)

In the example of the traveler, each *architecture* would represent a hypothetical trip. Depending on the level of detail, one trip architecture could consist of taking a taxi to an airport, boarding a plane, flying to a city and then taking another taxi to a hotel. Another architecture could be identical except consist of having a friend drive the traveler to the airport instead of the taxi. A third architecture might consist of taking a taxi to a rental car company and then driving a rented car to the same city and hotel as above. If the traveler was trying to save money, having a friend drive them to the airport might be an option, however if the flight was very early in the morning, the traveler may not want to inconvenience their friend and opt for the taxi instead. In MATE-CON, the decision criteria used by the traveler to choose one trip architecture over another (convenience, total travel time, etc) are referred to as *attributes*. In the process, each attribute is assigned a level of value, or *utility*, by the *decision-maker*. For each proposed architecture, the utility of each of the multiple attributes is calculated and combined into one final ranking by the Multi-Attribute Utility Function shown in Figure 3-B-2. When plotted on one graph, a traveler could then decide between a high-utility / high-cost set of trips and a low-utility / low-cost set of trips.

Depending on the level of detail required, and the analytical goals of the group, a team of 5 to 15 key stakeholders can generate a Multi-Attribute Tradespace for an entirely new design problem in two to six weeks. This platform then serves as the starting point and guide for a larger Integrated Concurrent Engineering team.

$$KU(\underline{X}) + 1 = \prod_{i=1}^{N} \left(K k_i U(X_i) + 1 \right)$$

Multi-attribute utility function ($U(\underline{X})$)

Single attribute utility ($U(X_i)$)

Normalization constant (K)

Relative "weight" (k_i)

Figure 3-B-2: The Multi-Attribute Utility Function (from Keeney, Raiffa, 1976)

One of the unique challenges of initializing a MATE project is defining the attributes. The team needs to work collaboratively with their customer to define 5 to 7 characteristics of the system that will enable the decision-maker to choose the most valuable system architecture. The set of attributes must be complete, operational, decomposable, defined over a wide range and independent of cost. The last two qualities are by far the most important, yet the most difficult for new designers to work with.

Within the world of product design, in past trade study or decision processes, performance objectives of the system often became obscured before they were even openly discussed. Whereas a customer may have a desire for a plane with a 13,000-mile range for example, he may believe that such an aircraft would be too expensive or too complicated and thus submit a requirement that is tempered by his own perceptions. In this scenario, the true desires of the customer will never be satisfied, and worse, he may never know what could have been available or how much such a system actually may have cost.

Other examples of attributes could be operational lifetime of the system, reliability, speed, payload capacity, data transfer rate or even manufacturing lead-time. Past projects employing MATE have focused mainly on technical performance attributes, but the process could readily be applied to the design of manufacturing systems, supply chains, customer relationships and even organizations themselves.

Once the attributes are defined, a utility interview maps the relative value of each attribute over its entire range. The interview can be facilitated by the use of a special software program that employs the lottery equivalent principle to determine a decision-maker's preferences under uncertainty. Since people tend to make decisions that maximize expected utility, the data obtained from this type of interview also reveals their risk preference for each attribute. A second interview then polls the decision-maker and reveals his or her relative preferences among the set of attributes. Entered into the Multi-Attribute Utility Function, these k-values are much more than a simple weighted-sum of the single attribute utility values.

The team then creates a set of system models (using Matlab or a similar simple code) that describe the system to the desired level of detail. In the MIT work, these models have been created in a modular structure so that, as the tradespace is explored, the team can go back and enhance the fidelity of the models as they zoom in around certain areas of interest. These built-in iterations allow the team to rapidly obtain preliminary results, check the validity and feasibility of their models and assumptions, then continue on to the desired level of detail (depending on budgetary and schedule constraints).

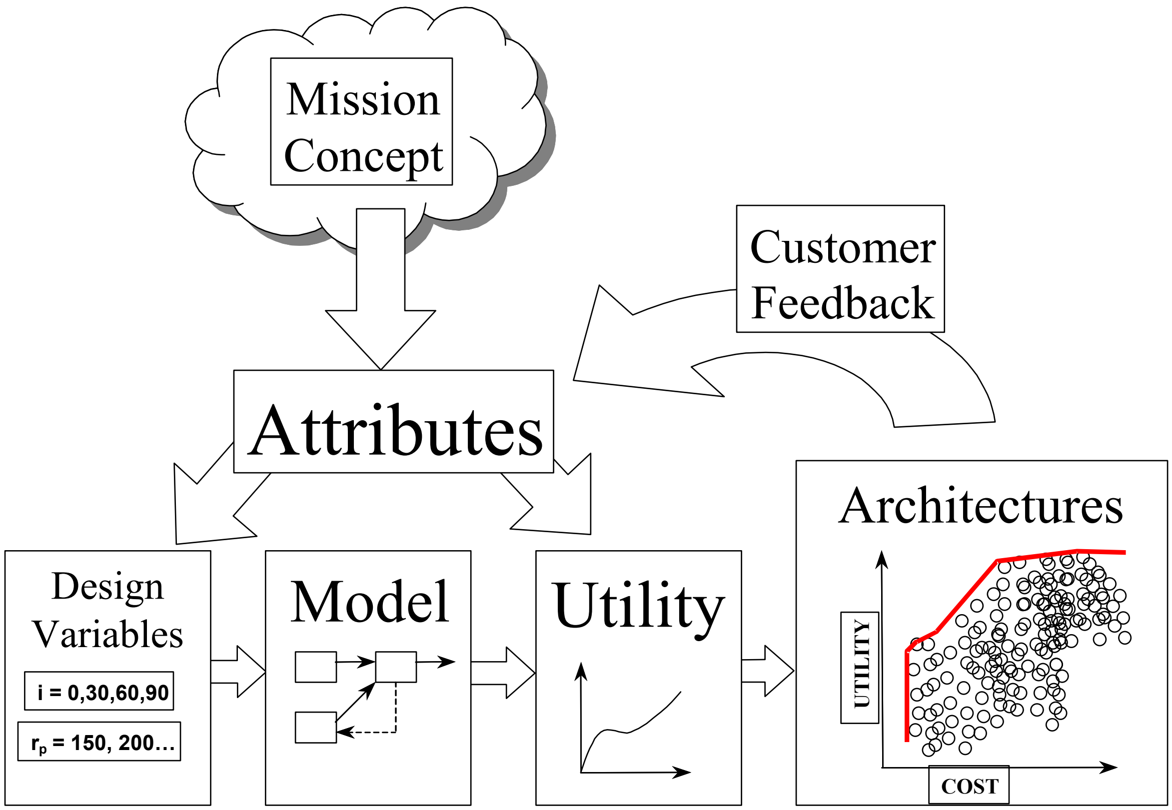


Figure 3-B-3: The MATE-CON Process

When the models are complete, a set of design variables is passed through the models. The number of variables depends on the time, computer power and requirements for detail given to the team. In a typical MATE process, approximately 10 to 20 design variables are used, each with two to five possible values. A computer generates the full set of all possible combinations of design variables, and each set (or architecture) is input individually into the models, and the corresponding attribute values are calculated. Each attribute value is compared to the decision-maker's utility curve and translated into a utility value, which is then input into the Multi-Attribute Utility Equation (Refer to Figure 3-B-2).

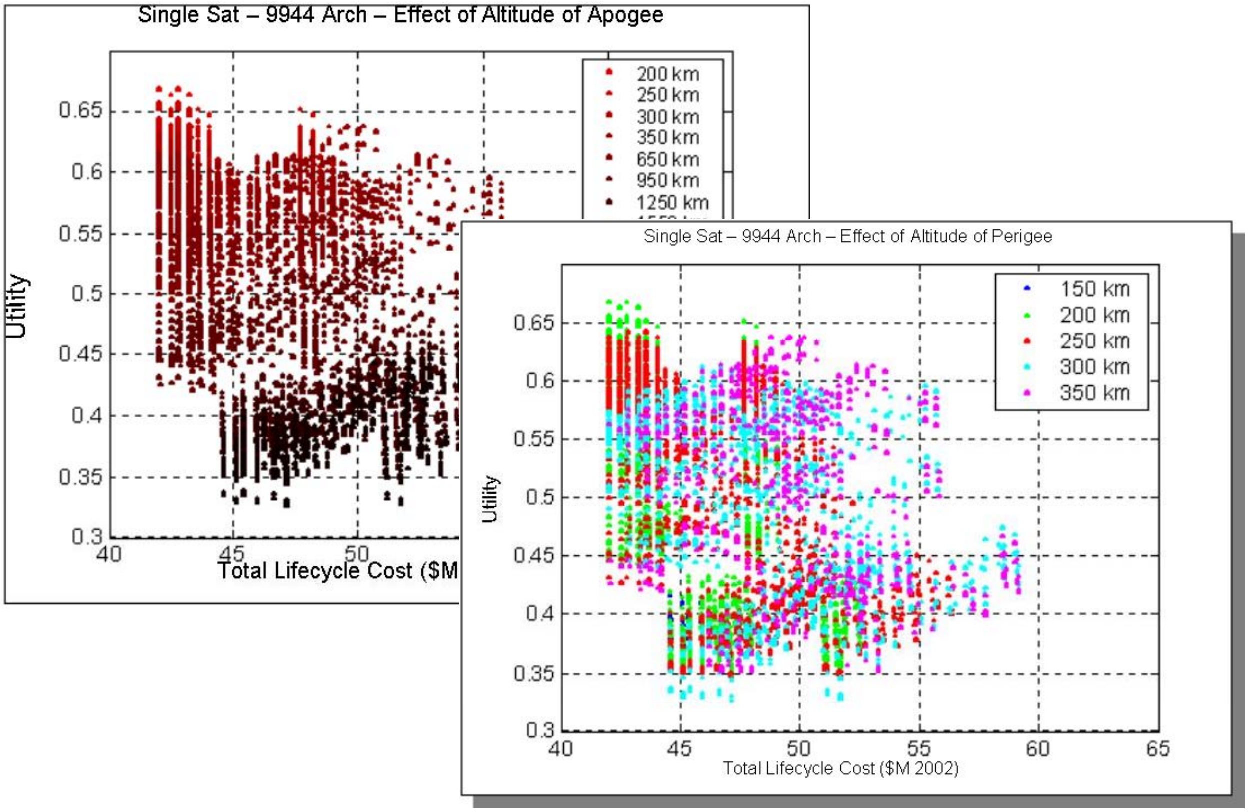


Figure 3-B-4: MATE-CON Output from MIT's Project X-TOS, May 2002

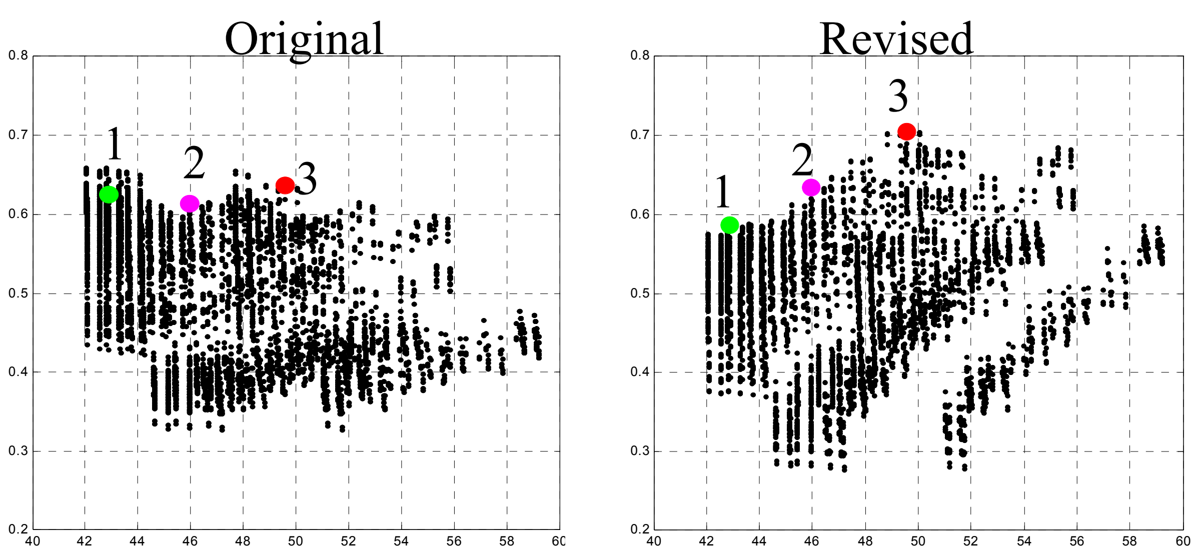


Figure 3-B-5: Original and Revised Results of MIT's Project X-TOS. Revisions made in response to shift in customer preferences (k-values). Same color dots represent equivalent architecture designs – attribute values were the same however utility values changed in response to customer preferences.

The corresponding Multi-Attribute Utility Value is plotted against the estimated cost for each architecture to generate a tradespace. The combination of the MATE and ICE processes at MIT has been referred to as "MATE-CON." Figure 3-B-4 shows the results of a MATE-CON team, "Project X-TOS," which examined possible mission architectures for an atmospheric density probe in the spring of 2002. The X-TOS team consisted of 15 graduate students who worked together in three 2-hour sessions each week. In addition, each member also performed about six additional hours of work outside the team sessions. Figure 3-B-5 shows some additional data analysis performed by the team exploring the sensitivity of the results to changes in customer preferences (same design architectures plotted against updated utility curves).

Although Multi-Attribute Utility Theory was developed over 20 years ago, only recently has the theory been applied in a real-time setting by the use of significant computational resources. The MATE-CON technique reveals a powerful new application of the process – far beyond the Utility vs. Cost plots displayed above.

Generating the plots is an iterative learning experience. No matter how skilled or experienced MATE-CON participants are individually, their collaboration uncovers new and exciting system solutions that would not have been contemplated using another design approach. As a team works through the process of choosing attributes, interviewing the customer(s), building and testing the system models, and analyzing the tradespace, they inevitably reach new levels of system intuition.

One common misconception is that the process yields an optimal "solution point." In fact, the process could be thought of as a new form of a "Design of Experiment" methodology – quickly and efficiently finding the underlying causes of a set of effects. The result is a Pareto Frontier of architectures that best satisfy the cost-to-performance tradeoff within the given physical and political limits. It is then up to the decision-maker(s) to determine the best approach given this new understanding of the complex system – this can be based on the maximum funds available or the minimum system performance that is acceptable.

The process elicits explicit conversations between designers, customers and the value chain that are as absolutely necessary as they are neglected in the current process. While each team member enters the process with individual perceptions about which attributes are more important and about the relationships between design variables and those attributes, MATE-CON brings about a systematic, objective method of evaluating the actual relationships with respect to the true customer preferences. Decisions are made in the open with full knowledge of the trades being made.

Tradespace Plots are dynamic vehicles for communication and learning. As the X-TOS case showed, customer preferences can and will change over the life of a project. Using MATE-CON, design teams can work together to anticipate the impacts potential changes could have on a particular architecture choice. If a change is requested or explored, the plot becomes the basis for a powerful discussion of the relative costs and performance trades being made.

In terms of presentations to managers and customers, the tradespace plot provides a new and interactive approach. Instead of weighing the merits or demerits of a handful of designs, a group can now discover the relative values that are created or negated by particular system requirements. If compromises must be made, options can be explored using "what-if" scenarios, and the costs of such changes can be quantified rapidly. For example, during Project X-TOS, the team needed to understand the effect that potential solar conditions would have on the performance of their proposed architectures. Figure 3-B-6 shows the results of their analysis.

MATE-CON Terminology			
Name	**Definition**	**Source**	**Example**
Design Variable	A technical system characteristic that can be changed to create a new architecture	System Designers choose the technical parameters that will characterize the system	Taxi vs. a Friend's car for ride to the airport

MATE-CON Terminology			
Name	**Definition**	**Source**	**Example**
Architecture	A unique set of Design Variables that describe one potential mission	One value of each design variable is chosen (such that the full set of all possible missions are explored)	A completely-defined trip (taxi – plane – taxi) or (friend's car – plane – taxi)
Architecture Attribute	A decision maker-perceived metric that measures how well a decision maker-defined objective is met and is independent of cost	Key Decision-Maker(s) communicate to the design team the most valuable features of the system	Duration of the whole trip, amount of luggage that can be taken, flexibility to leave at any time
Single-Attribute Values	The quantitative value of each attribute for a given architecture	A new value for each attribute is calculated by the system model for each architecture that is examined	For the (taxi – plane – taxi) trip, the total travel time could be 10 hours from door to door
Single-Attribute Utilities	A dimensionless parameter that reflects the "perceived value under uncertainty" of each attribute	Key Decision-Maker(s) are polled to create utility graphs for each system attribute. The Attribute Values are then compared to these graphs and translated into corresponding utility values	The traveler may need to arrive within 8 hours in order to attend a business meeting – thus a plane trip with 3 connections that lasts 12 hours total will not be of any utility to the traveler
Multi-Attribute Utility	A measure of relative usefulness for each architecture	All of the Single-Attribute Utility values are rolled together into one value for each architecture based on the relative value the decision-maker places on each attribute	The final value of a proposed trip to the traveler (measured on a scale of 0 to 1). The 12-hour trip would therefore be of 0 utility, while an 8-hour trip might be 0.5 and a 3-hour trip a 1.0 because it leaves time to prepare for the meeting.
Cost	Total Lifecycle cost of the mission	A new value is calculated by the system model for each architecture that is examined	Total cost of each proposed trip ($600 for the 8-hour trip and $2,000 for the 3-hour trip, for example)

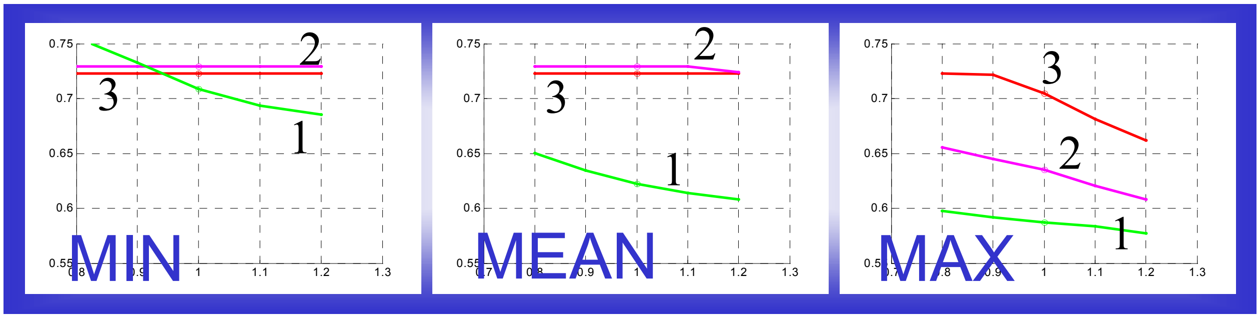


Figure 3-B-6: Sensitivity Study Results of MIT's Project X-TOS. At solar min, the utility of Architecture 1 (green) surpasses both Architecture 2 (purple) and Architecture 3 (red); while at solar max Architecture 1 has a relatively low utility. Architecture 3 therefore chosen because it was most robust to external uncertainties.

Section 3-C: PSI Analysis of ICE and MATE-CON

By itself, Integrated Concurrent Engineering is a balanced approach to the problem of complexity in product design. It successfully addresses the key elements of technology, people and process, but can still fall victim to the point-design paradigm.

Analysis of Integrated Concurrent Engineering (ICE)					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
✓	✓	✗	✓	✓	✗
Multidisciplinary design team works together in the same room to resolve system-level design and manufacturing issues.	Parametric models are continuously updated with the latest information and provide instant feedback about the impacts of potential design options.	A customer may be present during the concurrent design session, but typically, ICE teams focus on the superior technical performance this method allows them to achieve.	Key information is passed seamlessly from one designer to another. The final artifact is a complex system model that can be explored easily and accurately by subsequent teams.	Multi-disciplinary demographics of ICE teams are usually representative of most key stakeholders in the value chain.	ICE teams can also fall into the "point-design" paradigm. They often believe they can "optimize" their way to the best design.

With the addition of MATE, ICE teams can become well-rounded system design teams. In summary, MATE-CON:

- Captures thousands of architecture options in one place
- Promotes a rigorous examination of competing architectures before jumping to a point-design
- Aids in system-thinking by helping people to visualize the benefits and sacrifices of complex trade-offs
- Allows sensitivity studies to be run which help create more robust designs.
- Pushes a team to define customer values and justify each potential solution based on those criteria
- Guides a team dynamically – giving rapid and accurate feedback about new design ideas – during an Integrated Concurrent Engineering session
- Helps designers quickly gain an intuitive feel of very complex systems
- Provides an interactive roadmap for each design session
- Creates a common, visual language that helps elicit very meaningful conversations between customers, designers, and operations
- Sets a new paradigm in proposal deliverables – not just the best option(s), but why they are better than every single alternative (including the competition)
- A simple, objective framework is needed for communicating and analyzing different design options.

If successfully deployed, MATE-CON can meet and surpass each of the PSI framework criteria.

Analysis of MATE-CON					
Parallelization		**Standardization**		**Integration**	
Are independent processes are carried out simultaneously? (PROCESS)	*Do dependent processes receive information and attention just in time? (PROCESS)*	*Does the process systematically identify and eliminate wasteful efforts based on a customer-defined value system? (PEOPLE)*	*Does the process enable the team to streamline knowledge-transfer both in real-time during a project and upon completion? (TECHNOLOGY)*	*Does the process ensure consistent input and validation from the entire value chain? (PEOPLE)*	*Does the process objectively explore the full set of solutions? (TECHNOLOGY)*
☑	☑	☑	☑	☑	☑
(Same as ICE) Multidisciplinary design team works together in the same room to resolve system-level design and manufacturing issues.	(Same as ICE) Electronic parametric models are continuously updated with the latest design information and provide instant feedback about the impacts of potential design options.	Uses utility functions as a proxy for the customer's needs. Ranks potential product architectures according to customer value in order to seek best solutions to a very complex problem.	(Same as ICE) Key information is passed seamlessly from one designer to another. The final artifact is a complex system model that can be explored easily and accurately by subsequent teams.	(Same as ICE) Multi-disciplinary demographics of ICE teams are usually representative of most key stakeholders in the value chain.	Solves the ICE "point-design" paradigm by opeing up the entier tradespace to the team. Value-generating relationships can be understood intuitively and then pursued.

Section 3-D: Characteristics of a Successful MATE-CON Team

Understanding the theoretical output of a MATE-CON process has been a great achievement. In practice, however, a clear vision for a high-performing MATE-CON team must be created and implemented accordingly. (Ulrich and Eppinger, 2000) adapted a set of criteria used to predict team performance in a product development environment:

- There are 10 or fewer team members.
- Members volunteer to serve on the team.
- Members serve on the team from the time of concept development until product launch.
- Members are assigned to the team full-time.
- Members report directly to the team leader.
- The key functions, including at least marketing, design and manufacturing, are on the team.
- Members are located within conversational distance of each other.

In their research of IPT's within the aerospace industry, Klein and Susman (1995) identified a number of attributes associated with successful teams. For so-called "low-risk" projects – those involving mostly existing technology and processes – such as the recurring design of a product family or the design of a new system using a well-defined MATE-CON process, the following items were identified:

Program Management Factors:

- Program managers with more influence than functional managers
- Teams with more influence than functions
- Participation of both functional and program management in evaluations
- Evaluation weighted toward project goals

Group Processes:

- Agreement among team members on project goals
- Satisfaction among all team members in product design decisions
- Decisions shared between team leader and teams
- Decisions shared between program managers and teams
- Entire team influences decisions

After an ICE team process was implemented at the Aerospace Corporation, (Neff and Presley, 2000) noted several "environmental factors that help foster creativity:"

- Trust and respect for each other
- Individuals believing they can speak up without fear of punishment or reprisal
- An atmosphere of experimentation and craftsmanship
- Failure is not treated as a crime
- Supportive management
- Low levels of cynicism and harsh judgments

At NASA's Jet Propulsion Laboratory (JPL), the implementation of an ICE design environment had a dramatic impact on the productivity and cycle time of new conceptual design studies. The team's work capacity increased from an average of 10 studies per year, to over 45. The average duration of a study dropped from over 26 weeks to 2 weeks, and the typical cost of a study was slashed from $250,000 to about $85,000 (Wall, et al, 1999).

The cases referenced above also noted that a high-performing MATE-CON team should incorporate not only a strong structural design, but it should be well-supported by a management team that shares a clear vision of the potential benefits of the process and is willing to protect and nurture the team while it breaks new ground. The project sponsor should set clear expectations for the MATE-CON team, monitor their progress, and reward them accordingly (Klein and Susman, 1995). The sponsors should also create a forum so that the team can openly address difficult issues and constantly strive to improve their processes and enhance the value they deliver to their internal and external customers.

Aside from the external influences MATE-CON team is subjected to, the character traits of individual team members can influence the quality and efficiency of the process outputs. The nature of the work that is carried out during MATE-CON sessions and the intense preparation required to support the process call for a balanced blend of technical competence and teamwork skills.

Instead of re-arranging when work is done, and by whom, MATE-CON actually changes how people work. To many participants, the new process frees them from years of frustration and limitation. It gives them insights into the entire system that were never before possible, and opens their creative floodgates. To others, however, working in an ICE environment is stressful, noisy and inconsistent. These team members cycle between being very busy with a particular task, to suddenly being idle while others resolve unrelated issues. They feel constrained by the rigid script of a design session (because they cannot take the time to explore every item in the way they had been used to) or by being forced to operate a spreadsheet that was created by another designer and is not intuitive or is based on unfamiliar assumptions.

These very strong reactions indicate that potential team members must be carefully selected but also afforded the opportunity to fully understand the new type of work they will be asked to perform. The highest performing ICE team members typically break free of their particular subsystem and pitch in to help the team in any way possible. They display "a temperament for conceptual design, the right technical skills, a desire to be involved and to contribute, a "can-do" attitude, a willingness to make time to be involved, ability to work well on teams, and a collaborative nature." (Neff and Presley, 2000)

Therefore, the characteristics of a successful MATE-CON team will be as follows:

- Strong Team Leadership
    - OLD: Results and Budget-oriented
    - NEW: Disciplined, rigorous, yet overwhelmingly supportive **and** consistently able to deliver results on-budget
- Application of the appropriate Technology
    - OLD: Technology can solve complex problems
    - NEW: The tools we use must be powerful yet intuitive, timely and universally accessible **and** incorporate the latest technology
- Innovative, motivated People
    - OLD: Team Member Specializing in X
    - NEW: System Designer / Value Creator **and** technical expert
- An Inclusive, objective, efficient and constantly-improving Process
    - OLD: Turn Money into Project Deliverables
    - NEW: Transform Time into Valuable Insights **and** deliver reliable outputs

Chapter 4: ICE – In Practice, An Organizational Quagmire

The previous chapter detailed the theoretical advantages that the MATE-CON process has over other popular forms of Concurrent Engineering. But if it is a superior approach to the design of complex systems, why hasn't it become more widely adopted? Is there an inherent conflict between the paradigm of decomposition (that is the basis for most modern organizational structures), and the philosophies that power Integrated Concurrent Engineering and MATE-CON? In order to answer these questions, the implementation of these processes in a real organization must be studied in depth.

Section 4-A: Recent ICE Implementations

Several major organizations have implemented Integrated Concurrent Engineering (ICE) processes in the last 5 years. Their uses range from designing small satellite payloads to large "system-of-systems" communication architectures. While each of these design facilities have been highly successful in achieving their Technical objectives, they each dealt with difficult People and Process issues (Heim et al, 1999), (Parkin, et al, 2003), (Sanders, 2002), (Wall et al, 1999), (Neff and Presley, 2000). Before presenting the detailed case study, the following general lessons can be learned:

- All teams found that a dedicated, "standing" design team was the most powerful approach. True process improvement requires a team to practice a process many times and then to have the authority and accountability to make positive changes.
- The physical layout of the design "home room" was just as important to the team's success as the information-exchange architecture. Communication happened verbally, non-verbally and electronically.
- Strong, passionate leadership was essential.
- The highest-performing team members were those who were able to be flexible and look at the whole system rather than reverting to being subsystem experts only.
- All the teams started with a self-described "crude" information exchange process. They improvised and innovated as they progressed rather than waiting for a large, complicated new software system that was everything to everyone.

Section 4-B: Deep Dive: Overview of Project RTCE

In the last quarter of 2001, a mid-level manager at a large US aerospace company assembled a product development team to create an innovative product design process. This "Real-Time Concurrent Engineering" (or "RTCE") team would be chartered specifically to apply the concepts of Integrated Concurrent Engineering (ICE) developed at CalTech, JPL, MIT and Stanford. In rapid succession, the new RTCE team built customized design tools, validated their technical performance and began generating high quality proposals.

An outside expert initially facilitated the efforts of the RTCE team. The courageous manager who sponsored the project obtained internal development funds based on anticipated efficiency gains in his new product design department. His staff consisted of approximately 75 engineers who were each assigned in a matrix fashion from their functional group on a rotational basis. Although all of these specialists were co-located in the product design department, each retained accountability to their home department, and reported to their functional managers for performance evaluations. This department was essentially a product-development IPT.

The team began by meeting together to identify the entire set of information that would be exchanged during a design session. This exercise began with each subsystem representative listing a very specific set of variables that were required to design a standard product. Other subsystem representatives then signed up to provide the data for each variable during the session. The result was a massive table with several thousand pieces of information that, in the past had all been exchanged manually. Immediately, the team became energized – they realized that they would never again want or have to design products using their old process.

After the needs-identification was complete, each subsystem designer was then tasked with creating a design tool that could translate the requested inputs into the outputs necessary to create a preliminary design. This process took approximately three months.

Figure 4-B-1: Photo of the Real-Time Concurrent Engineering Team at work in their Home Room

Realizing that the new way of working together would encounter resistance from many different parts of the organization, the sponsoring manager put together a comprehensive implementation plan and budget. He met with some senior leaders in the company and passionately obtained their buy-in for the first stages of development. He then challenged his best employees to help him make the concept into a reality. His personal dedication to the new process sent a clear signal to all involved that the RTCE project had absolute support.

The next phase of the implementation involved a technical validation of the new design method. The team leader announced a series of weekly meetings in which the new system would be used to design a product that the team had designed manually in the past two years. This approach proved to be extremely effective on a number of different levels.

By beginning with very simple designs, the team could get a 'first-draft' of their new tools up and running very quickly. Instead of working for months to develop complex models that could be used for every possible design scenario, team members were quickly able to understand what worked and what didn't. Additionally, the element of 'peer pressure' was introduced to the team – if one team member showed up unprepared for a validation meeting, he or she knew that they would be holding up the entire team. But, by practicing on designs that were familiar to all of the team members, the anxiety of working together in a new process was reduced significantly – the team avoided technical uncertainties and could thus take their time and focus on the group process and their new system-level perspective. Finally, as the team worked through the validation process, their confidence and excitement grew steadily – they were fully energized and more than well prepared by the time they used the new RTCE process on their first real design challenge.

Since the RTCE team was able to focus its work life around a very specific set of tasks, they were able to refine their process over time. The team is currently capable of producing a new product proposal in approximately 30 days (compared to 45 days or more using the traditional approach). Within this time frame, the RTCE team is also now able to compare and contrast approximately 7200 different design parameters between each of ten or more preliminary technical designs in order to arrive at a final design. Using their previous method, they traded 10 to 20 performance characteristics of two or three preliminary ideas before moving on to analyze their final design in detail.

Section 4-C: Deep Dive: Current and Emerging Benefits of RTCE

Between June of 2002 and July of 2003, the author performed a number of surveys of key team members and an extensive set of interviews of team leaders and company managers – including the company President, Chief Technology Officer and three Vice Presidents. In addition, more than ten full-length concurrent design sessions and numerous leadership meetings were witnessed first hand in order to gather observational data on the performance of the RTCE team.

An analysis of these data reveals that the RTCE process has dramatically improved the new product design process at the company. It creates value by increasing the Quality of the company's designs and manufactured products, the Speed at which they are created, by fostering product and process Innovation, and enhancing Learning opportunities.

NOTE: The following findings were based on anecdotal evidence gathered by interview, survey and observation. Refer to Section E of this chapter for quantitative performance metrics.

QUALITY: For each new product proposal, more design options are examined, and each is evaluated far more rigorously. On average, the team examines at least three potential design configurations using the new process. Each conceptual design consists of up to 7,000 standard design variables, which are input, calculated or otherwise determined. Each of these variables is stored in a database, and, because they are common to all designs, competing architectures can be compared directly to one another.

Each designer has continuous access to latest published design variables and assumptions. In the past, weekly design coordination meetings were held to update the team members on important design parameters. In between these meetings, subsystem designers often communicated informally to trade information via e-mail or hallway conversations. Using this ad-hoc information-exchange architecture, however, it was not uncommon for team members to learn that the past week's worth of work had to be completely re-done because of a change made to another subsystem that they were unaware of.

In the new RTCE process, the team discusses details in real-time that could otherwise be overlooked or forgotten. During the course of the validation program and as new designs began to be completed, the team began to notice that there were a substantial number of items that were systematically addressed during each RTCE session that were often neglected in the previous, decomposed design method. They realized that the thoroughness to which each product proposal had previously been completed varied widely depending on the proposal manager and the particular budget or schedule for that project. The team was pleased to set a new and consistent standard of excellence in all of their deliverables.

Key suppliers and manufacturing personnel could be more easily included in the earliest stages of the design. Although the RTCE team has not yet tapped into the huge reservoir of potential design improvements that could be realized by pulling downstream suppliers into the conceptual design process, the modular structure of the RTCE process could easily accommodate their inclusion. Further gains will be made by the elimination of the hard hand-off that occurs between the new product design process and the initiation of the detailed design work done in other departments.

Currently, the detailed design engineers take the proposal generated by the RTCE team as proof that the product can be built, but start the design process from scratch because it is not in a format they can easily build upon and because they do not necessarily trust the output of the proposal team. This disconnect can account for up to 10% of the development time for each new product.

SPEED: In the world of competitive bidding, the reduced lead times for each proposal created by the RTCE process can become a strong competitive advantage. Often, the RTCE team is generating proposals for potential customers that have not completely frozen all of their design criteria. The ability to rapidly incorporate last-minute changes or ideas (without heroic over-time) increases customer satisfaction and allows the team to be the first to set a customer's expectations. As the company negotiates final contracts, the RTCE process has become a competitive advantage – the speed with which the team can incorporate the latest revisions into their proposed design gives the negotiating team more detailed information to share with the customer and more confidence that the proposed design can be turned into real hardware with the time and budget they base their final offer on. And during the negotiations, the fact that the company can now help a new customer rapidly work through a number of "what-if" scenarios as they develop their business plan leads to strategic advantages as well – the company is in a better position to match the needs of their customers with the standard designs that also fit their long-term corporate objectives.

Shorter programs are less expensive. The same number of people working on a team for less time simply saves the company money.

RTCE designs mature more quickly resulting in a program with less uncertainty and rework. Since the team is able to quickly converge upon a conceptual design that consists of up to 7,000 standard design variables, the risk of finding a major flaw in a proposed design is nearly eliminated. As mentioned above, using the previous method, the team often went a week without exchanging vital information. If these meetings were not highly organized, a design that was nearly complete could have to be completely redone because it was based upon false assumptions or incorrect data.

INNOVATION: In its ideal state, the RTCE process focuses on system optimization based on customer value – rather than sub-system optimization based on rigid specifications. The RTCE team has worked hard to develop and validate their worksheet models based on their desire to run smooth, efficient design sessions. In addition, the company has placed its future in the hands of a small number of standard product platforms in order to reduce manufacturing lead-time and cost.

These objectives compete, however, with the process' power to spark innovation based on the system-level visibility afforded to each of the team members. During a session that can include up to 25 participants, it is difficult for one or two designers to take the time to try out a new idea. If an entirely new class of products were to be designed, the current RTCE process would have to be started over from the beginning in order to create a truly innovative new product architecture. Due to the highly complex technical challenges involved, these efforts would have to be supported by a traditional R&D organization, however the work of that group can now be much more closely aligned with the needs of the company and its customers.

Sub-system specialists who may never have worked together have the opportunity to share ideas and seek out new solutions to historical problems – classic organizational barriers are broken. During idle time, the most effective team members will seek out their peers and attempt to work together to constantly improve upon the performance of the system. Many of them finally have the opportunity to see how other subsystems are designed, and to understand the underlying reasons for certain design or interface requirements. In many cases, team members found that requirements that were extremely costly or difficult for them to implement were simply passed down from previous product generations – through the Integrated Concurrent Engineering Process, they were able to ask the right questions of the right people and replace those highly wasteful legacies with innovative new solutions.

Participants take ownership in their process as well as their product. Over time, and with practice, the RTCE team has become highly proficient. They know the capabilities of their system and each other. They are proud to represent their individual functional groups, and have proposed numerous improvements to their process.

LEARNING: The system-level perspective provided by RTCE yields a tremendous viewpoint for each engineer and business staffer to understand the impacts of their decisions and work. Whereas each subsystem specialist used to only concern themselves with the performance of their particular section of the design and would work in isolation from each other, the team members now sit and work together. In addition, the top-level performance metrics are constantly displayed – team members have instant feedback as to the impact their design decisions have on the performance of the overall system.

Dynamic models allow each new team member to "try-out" numerous what-if scenarios quickly and realistically. Due to the parametric nature of the models that the team built, new ideas can be evaluated easily and objectively rather than being shunned by managers who in the past did not have the time or resources to examine them. This new capability has a tremendous impact on the depth of knowledge that team members possess. They now have the opportunity to gain a more intuitive understanding of the system and the interactions of their particular subsystem as well, rather than being analysts who simply run the same set of equations over and over without ever really understanding the alternatives or underlying behavior of the system.

New ideas are evaluated objectively rather than subjectively (opinions based on status or perceived cost). In the past, many ideas put forth by new engineers were also rejected because higher-level engineers or managers already had a mental picture of what the final system would look like. This "design-by-seniority" approach tended to produce products that were all very similar to each other and that always contained the same set of subsystems no matter what. Although this conservative method produced products that were highly reliable and predictable, it discouraged the brightest and most innovative engineers – they tended to get discouraged and sought out more innovative jobs. This not only hurt the company in the short term, but also could have the effect of creating a vacuum of talent that could be particularly damaging when the current group of senior engineers retires in the next few years. The introduction of the RTCE process helps younger engineers raise their voice and show the validity of their ideas in an objective forum. This ability encourages them to continue to introduce new ideas and to be recognized for them.

Section 4-D: Deep Dive: Problems with RTCE

Unfortunately, by the winter of 2002 / 2003, circumstances surrounding the RTCE team were beginning to threaten its performance gains. At the same time the company developed the RTCE project's capabilities, the company's key markets began to sink – customers were delaying orders already in progress and withdrawing from talk of any new contracts. This created tremendous pressure on the RTCE team from all sides. The company experienced a net loss and was forced to lay off nearly 50% of its work force.

Besides the obvious emotional impacts, these circumstances masked the efficiency gains that the RTCE team had fought so hard to win – since people had less total work to do, were uncertain about their future employment prospects and genuinely wanted to help the company win more new business, they spent more time on each individual project than was necessary. By simply measuring the total cost of each new design, the managers were unable to see the improvements made by the team in the efficiency of their conceptual design process. Figure 4-D-1 shows that when the total length of the new product design process was held the same, the savings created by a more efficient preliminary design process were offset by other work. Thus the ROI metric commonly used as a measure to determine if the RTCE team should receive more funding did not reflect favorably on the work of the team.

Aside from these market-related problems, the RTCE team's rapid ascension created some unique and particularly challenging organizational and political problems within the company. These issues must be addressed in order for the team to achieve its ultimate goals, but are also of particular interest to other teams that may be planning to implement a similar real-time concurrent engineering process.

Organizational Structure: Figure 4-D-2 shows the current structure of the RTCE team's company. The manager of the Product Development group initiated the RTCE project, which is a part of the Systems Engineering Division. This was a logical place to implement ICE techniques – this department performed nearly 40 new product proposals each year, so there were tremendous opportunities for process improvement.

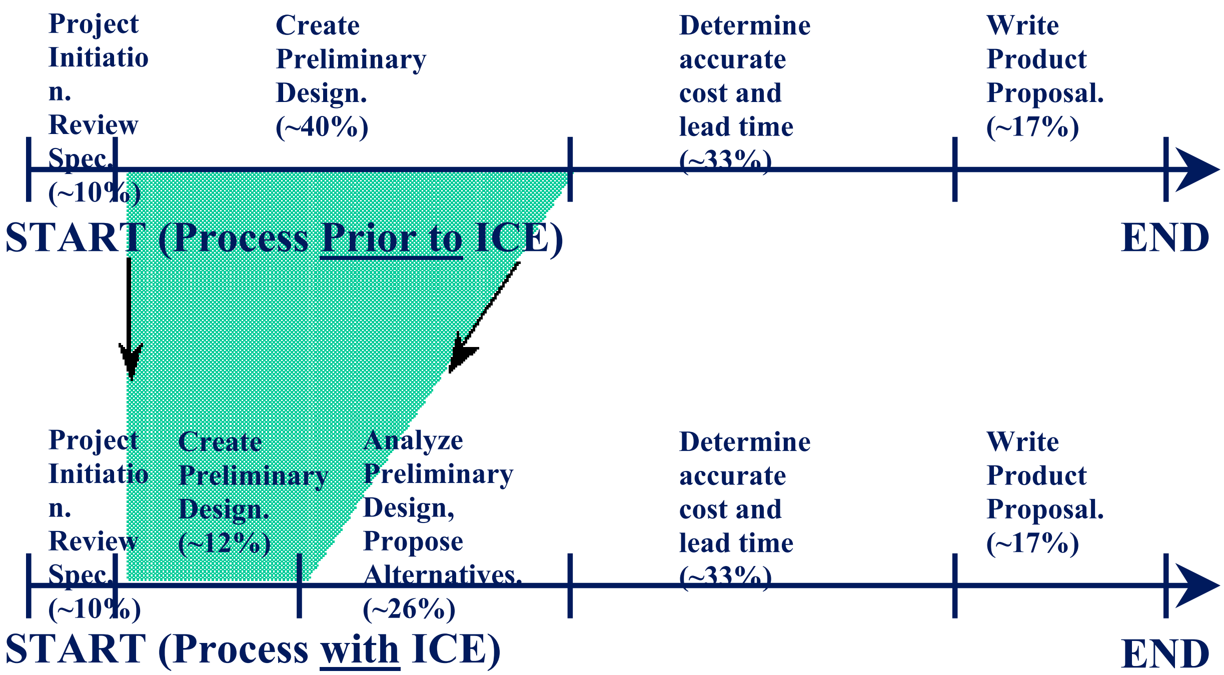


Figure 4-D-1: Timeline of the RTCE Team's typical project prior to and after the implementation of ICE techniques. The team found alternative activities (such as analyzing the design in more detail or proposing and analyzing more design options) to fill the time that was freed by a more efficient preliminary design process.

By June of 2002, all new product proposals were run through the RTCE team and its process. As the impact of their work began to reach other parts of the company however, the team began to encounter some resistance. For example, the marketing group was directly in touch with major customers but was not heavily involved in the development of the RTCE process. Although the RTCE team received detailed product specifications, they often had questions or needed market guidance during their concurrent design sessions. The marketing managers that participated actively in these sessions helped the RTCE team produce superb results. Alternately, some market

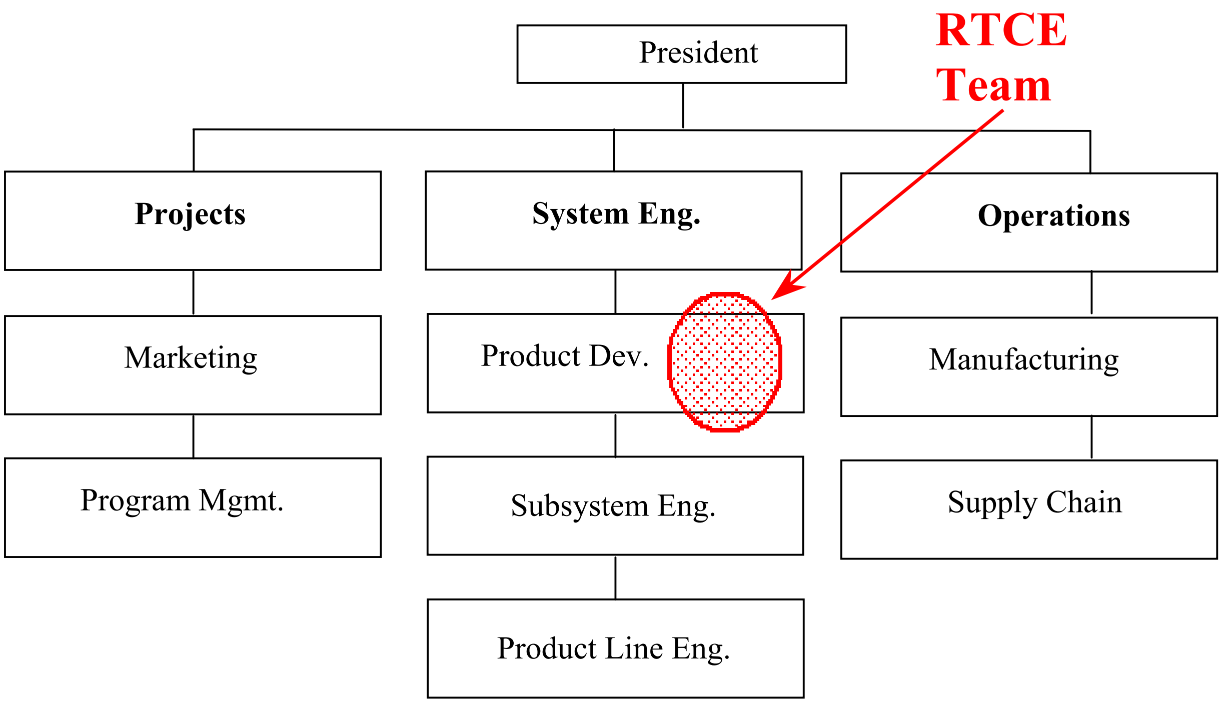


Figure 4-D-2: Organizational Structure of the RTCE Team's Company showing the home department of the team.

managers felt that design sessions were a waste of their time and did not show up for them or left early – this left design engineers frustrated and even led to wasted time and rework.

Similarly, the operations division was only indirectly linked to the RTCE team through one or two team members. This was the result of a scoping decision early on in the RTCE project (the effectiveness of the team began to trail off as the number of participants in a design session grew past about 15 people), but began to negatively impact the company's new product offerings because their input came too late to have dramatic impacts on cost or lead time. Figure 4-D-3 illustrates the effects of the barrier between the RTCE team (who performed the Preliminary Design tasks shown in the bottom third of the diagram) and the Operations group (who performed the Detailed Design and Manufacturing and Test tasks shown in the middle and top thirds). Note that there were other barriers within the operations group as well.

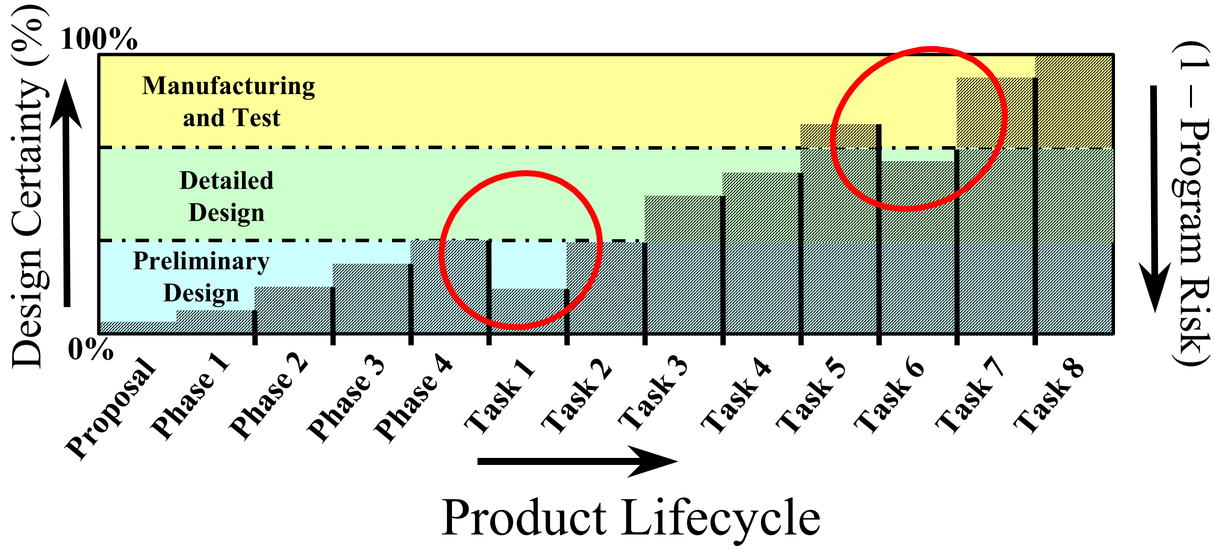


Figure 4-D-3: Notional Diagram of a typical product lifecycle at the RTCE Team's company. Systemic barriers can create large amounts of rework and lengthen the schedule because the information produced in one phase is often not in the form that can be easily used by the next, or work is redone because of mistrust or miscommunication.

One of the long-standing goals of the RTCE team was to implement a "grass-roots" cost model that would allow them to accurately weigh competing design options in real time. In the meantime, the team employed a cost estimation model based on historical data that was adjusted by the team members' estimates of relative complexity. A poll of RTCE team members taken in July and August of 2002 revealed that designers had an average "confidence" in the current cost model of 2.69 (on a scale of 1 to 5). To compensate for this, each proposed design was submitted to the operations group for a detailed cost estimate – an effort that took nearly two weeks and was very expensive.

As mentioned previously, RTCE team members still reported to their functional managers for administrative and evaluation purposes. When the sponsoring manager's overhead budget and the R&D funds began to dwindle, each team member was asked to continue working on their home department's portion of the RTCE project using the overhead accounts of their functional managers. Although several of the team members felt very strongly about the continued success of the project and lobbied their managers successfully, many functional managers were unwilling to support what they perceived as another manager's pet project with their own limited funds. The sponsoring manager responded by inviting the functional managers to participate in a

RTCE design session so they could see first hand the value of the new process – only a small percentage accepted the offer.

Senior Leaders within the company were aware of the organizational issues that were affecting the continued success of the RTCE team, but disagreed about how to proceed. They clearly saw the need to break down barriers between the different divisions but felt that other initiatives would have a more immediate effect on the short-term profitability of the company, and thus shifted more resources to those projects than to the RTCE team.

The RTCE team was also having difficulty prioritizing the issues they faced because they wanted to convey a positive message at all times. They were afraid that if they highlighted the problems, they could risk losing the support they already had. Additionally, it was hard for them to articulate the value of their process in terms of the strict return on investment (ROI) calculations that senior managers insisted on. The RTCE leadership had competing ideas regarding the benefits they had shown and the justifications for continued investment.

Organizational Culture: The shift to real-time concurrent engineering had a dramatic impact on the roles and responsibilities of each team member involved. RTCE team members were initially excited and motivated – many stated that they would never be able to do their jobs in the traditional manner ever again. There was a general euphoria that surrounded an innovative new way of doing business in the first months of the project. Over time, however, technical challenges, market conditions and organizational changes all took their toll on project morale. Interviews with team members elicited the following:

> "I felt that I resolved some on-going questions w/ my counterparts. [The RTCE process] provides a great opportunity for open discussion"
>
> "Received a good look at the design concept - received really good interaction from [the project manager]"
>
> "Since I had no schedule input, I felt like I wasted 1 to 2 hours of my time listening to schedule discussions"

> "People were forced to sign up for previous aggressive schedules w/o time to review justifications"

RTCE Team members were also asked to rate the level of participation they felt they had displayed during each concurrent design session (see below). These data revealed that even though RTCE members were doing their work together and sharing information electronically and in the "around-the-room" format, nearly half of them did not behave differently than if they had been working in their own offices.

> 17% said, "Focused only on my client (design spreadsheet)"
>
> 48% said, "Talked to one or two other people"
>
> 26% said, "Solved a minor problem (group of 1 or 2)"
>
> 0% said, "Solved a major problem (group of 3 to 5)"
>
> 4% said, "Helped entire group work through an issue"
>
> 4% said, "Was involved in a major design decision

By the end of the summer of 2002, the growth of the RTCE team passed through many phases and was beginning to impact more company stakeholders than originally anticipated in the team charter. As its boundaries expanded beyond those directly involved, certain perceptions – based on the paradigms of the existing organizational culture – arose:

Myth #1: "RTCE is a great new tool for the company. Once this team is finished developing it, we can deploy it to many other divisions to realize similar gains."

> **Facts:** Each individual toolset is highly customized and serves merely to enhance the effectiveness of each designer – allowing them the freedom to try out new ideas quickly and work together to find innovative solutions to unexpected problems. These toolsets evolve over time, and their strength comes from the fact that they are not just "plug-and-play" spreadsheets. Real-time concurrent engineering is a process – not a technical tool – that is only as powerful as the team running it. To be effective, the team must first learn a new way of working together, define their unique design variables, build and

validate their client models, then practice, learn and adapt. Any team is capable of becoming a high-performing RTCE team, but it will not happen over night.

Myth #2: "RTCE is going to save us tons of money because it automates the design process"

Facts: As one practitioner of ICE put it: "Computers cannot replace people in conceptual design. Rather, a good information system supports human strengths and compensates for human weakness." (Neff and Presley, 2000) One of the company's key strengths throughout its history has been the superb designs its engineers produce. Although Lean concepts and new processes such as ICE can help designers become far more efficient and effective, the need for creative human intuition is actually far more necessary in the new business process than in the old. Attendance at a real-time concurrent engineering design session proves instantly that there is nothing automatic about designing a 100 Million Dollar piece of highly customized technology.

Myth #3: "RTCE is dangerous because it creates 'template engineers' who know nothing about the complex hardware they are designing."

Facts: Fine balances between knowledge re-use and innovation must be drawn and constantly monitored. Although ICE techniques find a great deal of their efficiency in the fact that designers can quickly make use of complex analytical tools and historical databases that were prepared ahead of time, teams have found that the spreadsheets they go into a session with must be as flexible as they are accurate. If a designer enters a real-time concurrent engineering session thinking that his only job is to man his client, then that person might as well not be there. The most powerful solutions come from discussions between different designers regarding a difficult problem, not from a pull-down menu.

Myth #4: "RTCE designs cost just as much as traditional designs – there's no payback for the R&D money we invested."

> **Facts:** The metrics presented in Section 4-E show that the cost of a new product design using the RTCE process is about the same as it was using the previous method. However it has become clear that the quality of the work output by the team is substantially higher. Due to the nature of the process, teams are able to uncover hidden inconsistencies that otherwise would have not been addressed until weeks or months later in the detail design process. In one instance, the RTCE team tested this theory by repeating the design effort of a product they had done using the traditional method. The actual team members and the initial specification were the same – the only difference was the design process employed. The results were dramatic. The RTCE team uncovered a number of major errors and oversights in their initial design.

The increased depth of detail and exploration early on in the design process not only leads to a design with lower risk of technical failure, but also eventually means less work and rework for the detail design team. Applying ICE techniques, concurrent engineering teams now have the opportunity to examine more design options and inspect each one at a higher level of fidelity. The team can then openly and objectively select the best design for the particular customer, and then more easily communicate in a proposal what was chosen and why.

Leadership: Just as the senior management struggled to understand the current and future capabilities of the evolving RTCE team, the team leadership dealt with similar issues of vision and scope. This small group was faced with a number of important decisions and forced to prioritize their own limited resources.

Among the most pressing matters was the roster of the RTCE team itself. As mentioned previously, the original team was composed of the subsystem engineers who had been assigned to the product development center for their technical expertise. Although they represented the most important subsystems, they did not represent all of the specialized functions that were required to complete a final design. They had excelled in positions that allowed them to represent their own functional groups and to coordinate the design activity within their own groups. In the new team however, these individuals were being asked not only to make binding decisions in real time regarding their subsystems, but also to seek out and correct system-level problems that they had never before been exposed to.

The RTCE leadership worked to motivate these team members and to guide the team by expressing their expectations through group and individual "roles and responsibility" statements. Unfortunately, the political and organizational boundaries that separated the team members from the rest of the engineers and technicians who would be doing the detailed design work after a contract was won, could not be overcome by motivation alone. The team was aware that in many cases, after a contract was signed, the detailed designers disregarded their work and began the design process from scratch because they did not understand or trust what was done during the conceptual design process.

But within the team, were the leaders pushing the members to change too quickly, or did they just need to have a fundamentally different type of person assigned to this new job description? One manager suggested that the team should be comprised of younger engineers who were more comfortable working with the complex ICEMaker spreadsheets that had been designed. This team of "learners" would be able to rapidly understand the system they were working on and quickly iterate to a solution that best met the customer's needs for any particular project. Others argued that the team should consist of more experienced, senior experts. This team of "knowers" would be better able to come up with designs that would be robust, manufacturable, and built upon the company's vast history of technical achievements.

The leadership also pondered the outside commitments team members had to their functional managers. How could they expect the team members to think and act with system optimization as a goal when they were going to be evaluated, given raises or even laid off based on the performance evaluation of another manager with a set of priorities centered on optimizing their own subsystem? Unfortunately, the leaders of the product design group spent a majority of their time in meetings and did not take the time to discuss these difficult issues individually with the team members. Although the leaders felt that these were systemic issues that arose from company policy which could not easily be changed, the fact that these issues went un-discussed caused a great deal of anxiety and frustration among team members.

Next, the RTCE leadership had to decide how to obtain more funding for their program and where it could be applied most effectively. There were clear differences of opinion in this arena, and the sponsoring manager tried to give the team leaders the autonomy to make a decision based on their own vision, however without clear authority given to one member decisive action was not easily taken. One side advocated strongly to add CAD modeling capabilities so that team members could visualize complex assemblies and create more complete designs during each session. This effort would involve subcontractors creating libraries of standard parts – an expensive and lengthy proposition, but one that could add great strength to the team. Others desired improvements to the cost modeling or additional functionality for each subsystem client. Each option needed to have its cost and return on investment estimated in good detail.

Finally, the RTCE leadership wanted to measure its progress using metrics. They hoped that an analysis of labor hours spent, design completeness or the number of options examined would provide conclusive evidence of their positive impacts on the company. The initial data were inconclusive, however. It showed that the potential value RTCE could add to the company could only be realized by increasing the scope of the process – beyond preliminary design and into detail design work and manufacturing. The team leadership used these metrics as aids in decision-making however and did not attempt to set targets so that the RTCE team could monitor its achievements on a continuous basis.

Financial: The last major category of organizational issues that the RTCE team encountered involved money. As mentioned above, internal R&D funding was limited due to the market conditions and the financial position of the company. Although the bold move taken by the sponsoring manager to charge initial work to his overhead account had paid for itself handsomely in the form of a fully functional and value-adding process, more work needed to be done. Some members of the team felt that substantial expenditures were required to achieve the goals they had laid out. Others felt that a great deal of progress could be made using a "coordinated-individuals" approach – having people work on process-improvement as they performed value-added work for each new project. Were there contributions that could be made by team members in their spare time? In the spirit of real-time concurrent engineering, wouldn't working team feedback / continuous improvement meetings a much more effective approach to the teams near term challenges than a centralized, rigid task list?

Personal and organizational incentives also played a large role in the actions of the RTCE team. The company operated under a system whereby R&D investments would be repaid over time by decreases in a department's allocated budget based on the projected savings of the projects that received funding. So, if for example, the RTCE team stated in a proposal that an investment of one million dollars would result in a 5% productivity improvement, the product development department would have their budget reduced by 5% the next year. This system was intended to instill a degree of fiscal discipline into the company, however managers were rarely on the lookout for projects that would result in their budgets being cut, especially if that meant they would have to lay off their employees as a result.

When an RTCE project came down to final pricing, the team always faced another handicap. Even though the team had developed some cost models that could be used to make rough-order-of-magnitude (ROM) estimates in real-time during the session (and validated their models to within a few percent), a formal costing effort would always follow their work. Due to company tradition, and in the absence of another sanctioned method, all new prices were based on historical prices. Once the team completed its technical proposal, it would be forwarded to most of the functional managers for cost estimating. Each would examine the relative complexity of the proposed project as compared to past projects. Some would then add in charges for new special projects they wanted to use the new program to pay for, and would add in their own padding to ensure that their department did not go over budget. A special cost team (separate from the RTCE team) would then collect all of the cost estimates, roll them together, apply the corporate overhead rates and mandatory profit contribution, and then present a final cost to the executive management. Because the conceptual designers were not involved in this process, and due to the manual process of communicating the design details and cost items, the cost that was calculated could be for a different design that the one actually being proposed. A special review board would then review the cost, the company's strategic and competitive position, and then recommend a price that would be offered to the potential customer. Using this method, the company was completely unable to match the reductions in price that their competitors were beginning to offer – they were unable to estimate and account for the potential savings that would be made due to the higher quality designs that the RTCE team had produced.

Lastly, the accounting system employed by this company (and all others who performed work for the Department of Defense), mandated strict enforcement of timekeeping and charge numbers. Employees were audited periodically to make sure that the time they spent at work was charged to the appropriate accounts. Once the R&D money for the RTCE project was depleted, this meant, in effect, that many employees sat idle or stretched minor tasks for other programs that were funded instead of working efficiently on both other work and RTCE. Team members were actually dis-incentivised from using their spare time to work on RTCE or help out fellow team members because they did not have a charge number to reconcile their work with. The implications for this system should be immediately apparent to any manager and were extremely disheartening to the RTCE team leaders.

Section 4-E: Deep Dive: RTCE Metrics

Despite the organizational impediments that have slowed the progress of the RTCE team, they have been able to show tremendous success in their first crucial year of operation. Since the RTCE process became the standard new product design process in March of 2002, the team completed at least 10 new product proposals. They have trimmed 33% of the lead time from their standard process, and are now capable of creating new designs in as little as 4 hours – compared to up to 4 weeks previously. The designs they do produce are of higher quality because they examine each option in greater detail earlier in the design process by sharing thousands of design variables in real time. The team also enjoyed very high morale early in its formation.

Over the course of this project, the author collected performance data on nearly 100 new product proposal projects. Due to inconsistencies in the data or missing data items, the list was reduced to 43 final project sets. These projects were sorted according to the project scope. A subset of 36 of these projects – those classified as "Major Projects" – were further classified into following categories: year, use of RTCE and the number of designs considered. In order to provide additional context, personnel data were obtained to determine the number of employees working on these projects at any given time. The following table provides definitions of the key terms used in the process metrics provided below.

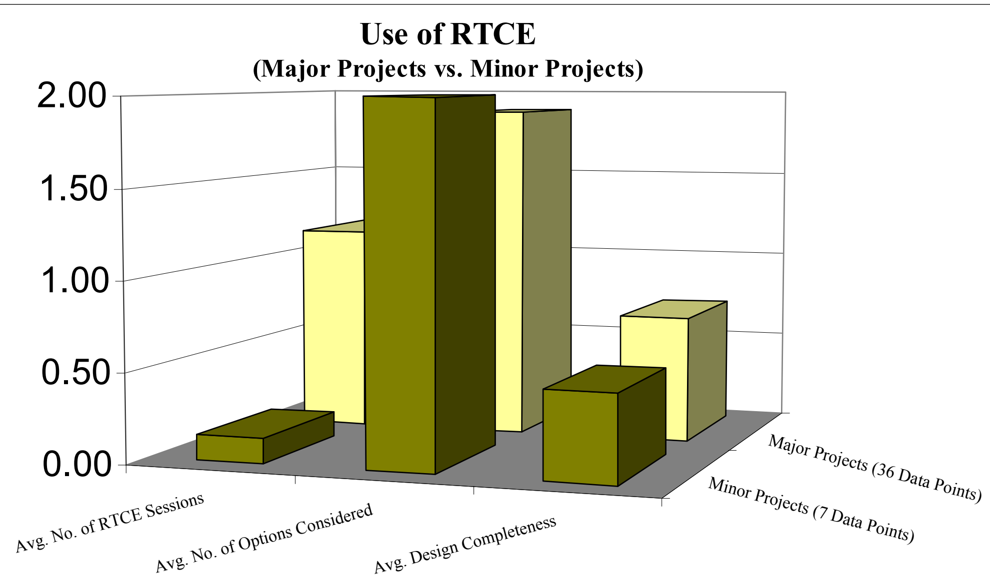
Definition of RTCE METRICS (Term: Definition)
Major Project: Formal proposal projects that begins with an official specification from a potential customer and results in the offering of a "Firm, Fixed Price" proposal for a highly refined new design.
Minor Project: A less formal response to a customer's inquiry. In response to a general, somewhat flexible set of initial requirements, the team submits a "Rough Order of Magnitude" (ROM) estimated price and one or more design concepts.
Without RTCE: This label refers to projects that were completed without the use of the Real Time Concurrent Engineering process.
With RTCE: This label refers to projects that included one or more Real Time Concurrent Engineering sessions in order to perform conceptual design work. This label does not eliminate the possibility that some design work was done using the traditional decomposition method.
Point Design: This label refers to projects that examined only one design architecture in detail. Although it does not exclude preliminary brainstorming sessions in which a number of potential ideas are discussed, in this scenario, the team chose one design option to pursue generally within the first week of the project.
Multiple Trades: This label refers to projects that examined two or more design options in significant detail. In most cases, these designs were presented either to the company's executive management, to the customer, or both.

Definition of RTCE METRICS (Term: Definition)
Projects: This staffing category represents direct hours billed for work on a specific design project (either a Major or Minor project as defined above).
Technology / Process Improvement: Any activity that was funded by corporate R&D money. This included development of new hardware and software for the company's products as well as new business processes such as RTCE.
Management / Overhead: All time spent on supervisory, support or special projects. As mentioned previously, between November of 2001 and March of 2002, half of the development of the RTCE process was charged as "overhead" in order to stimulate the project and make up for a lack of R&D money.
Average Number of RTCE Sessions: This label describes the average number of RTCE design sessions that were completed as a part of each project. Projects that did not employ the RTCE process, by definition have zero sessions.
Average Number of Options Considered: This category describes the average number of options considered for projects that had Multiple Trades as defined above.
Average Completeness Index: In the RTCE's home department, a set of standard tasks was to be completed for each new project (regardless of Major or Minor classification). These tasks were grouped and weighted according to their relative importance. At designated project milestones, the progress of the team was compared to the standard task list, and a project completeness index was calculated. The index ranged from 0 to 1 with a score of 1 signaling that 100% of the required tasks had been completed on the project in question. (It should be noted that many new projects deliberately planned for completeness index scores of less than 1 in order to save money or time. Alternately, many projects completed additional tasks that consumed project resources but did not increase the completeness index score.) These numbers were then averaged across each project category.
Average Index Cost: The cost of each project was obtained from the finance department. In order to protect proprietary information, the costs were all normalized. Thus an index cost of 1 represents the most expensive project undertaken by the group, and a score of less than 1 represents cost of each project as a percentage of the most expensive project. These numbers were then averaged across each project category. As a complete set, the average project cost index was 0.26.
Average Cost per Option: For each of the projects, the cost index number described above was divided by the number of design options that the project team considered (according to the definitions of Point Designs and Multiple Trades described above) in order to determine a secondary measure of productivity. These numbers were then averaged across each project category.

Definition of RTCE METRICS (Term: Definition)
Average Cost per Completeness: For each of the projects, the cost index number was divided by the completeness index in order to determine a measure of process efficiency. These numbers were then averaged across each project category.
Total Dollars: This number represents the total expense of a new product design project, it is the sum of costs that are assigned to the following categories: "design dollars," "cost dollars," "management dollars," as well as an overhead, or "G&A" charge.
Productivity: This metric is a generalized measure of the value-added work being accomplished within the RTCE's department. Monthly productivity is calculated by taking the total number of normalized project units (where each Minor project completed counts for one unit and each Major project completed counts for five units) and dividing by the average total staff level that charged their time to the "project" category.

Project Scope Metrics

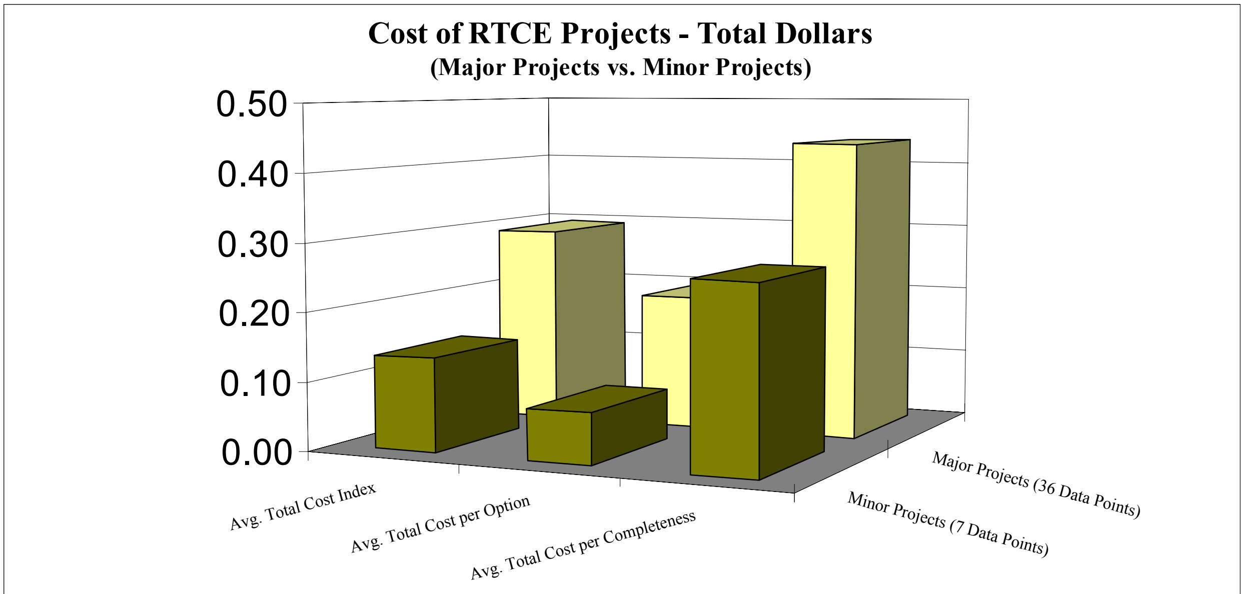
The data presented in Figure 4-E-1 comparing the process steps followed by both Major and Minor projects seem consistent with expectations. Major projects employed



	Avg. No. of RTCE Sessions	Avg. No. of Options Considered	Avg. Design Completeness
Minor Projects (7 Data Points)	0.14	2.00	0.49
Major Projects (36 Data Points)	1.17	1.89	0.72

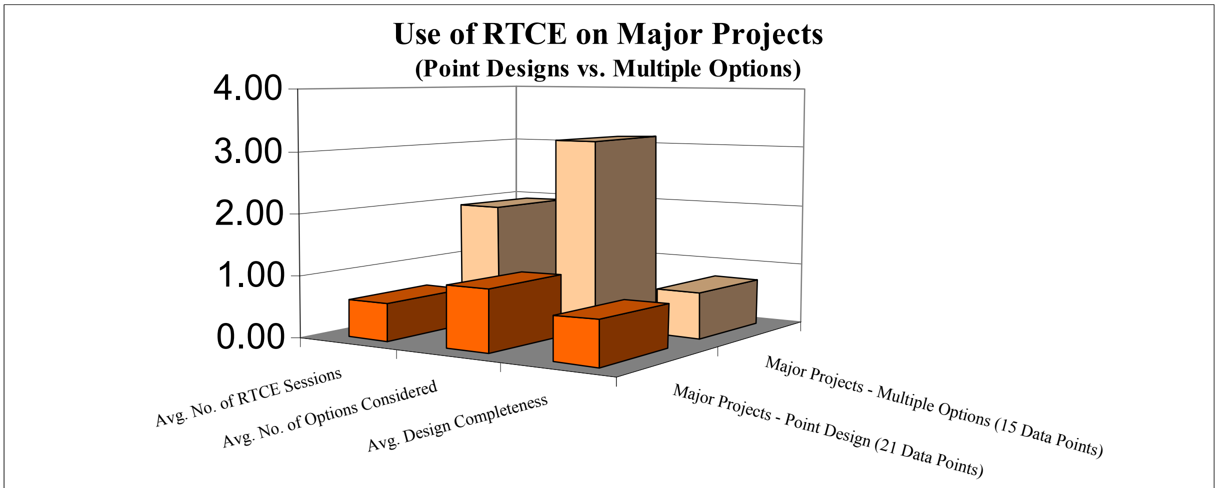
Figure 4-E-1: Use of RTCE – Comparison of the average number of Design Sessions, the average number of Design Options considered and the average Design Completeness Index between Major and Minor Projects.

more RTCE design sessions because they needed to examine design architectures in greater detail. However, Minor projects considered more design options because of their less formal project deliverables – it was easier for them to carry more options forward because the amount of work required to present an option was far less than the formal cost, schedule and technical proposals that were required for each Major Design Trade. Often, potential customers use the Minor projects to help shape their business plans, so they actually request to see more design options. On Major projects, customers may send the same requirements to many potential suppliers and usually accept only one design option with each proposal so that they can very clearly compare one supplier's offering to another. Also as expected, Minor projects had lower average costs, costs per option and costs per completeness indices. This trend can be attributed to the less stringent demands on the quality and depth of each design option that Minor project teams presented to each customer. Refer to Figure 4-E-2 for these data.



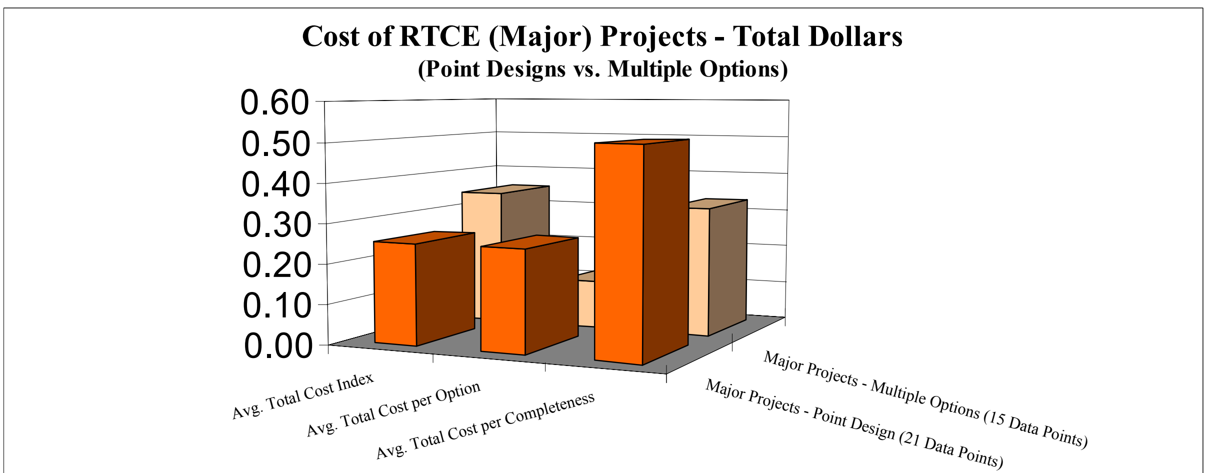
	Avg. Total Cost Index	Avg. Total Cost per Option	Avg. Total Cost per Completeness
Minor Projects (7 Data Points)	0.14	0.07	0.27
Major Projects (36 Data Points)	0.29	0.20	0.44

Figure 4-E-2: Cost of RTCE Projects – Comparison of the average Index Cost, the average Cost per Option and the average Cost per Completeness between Major and Minor Projects



	Avg. No. of RTCE Sessions	Avg. No. of Options Considered	Avg. Design Completeness
Major Projects - Point Design (21 Data Points)	0.62	1.00	0.70
Major Projects - Multiple Options (15 Data Points)	1.93	3.13	0.74

Figure 4-E-3: Use of RTCE on Major Projects – Comparison of the average number of Design Sessions, the average number of Design Options considered and the average Design Completeness Index between Major projects that examined only one design option (a point design) and those that explored multiple options



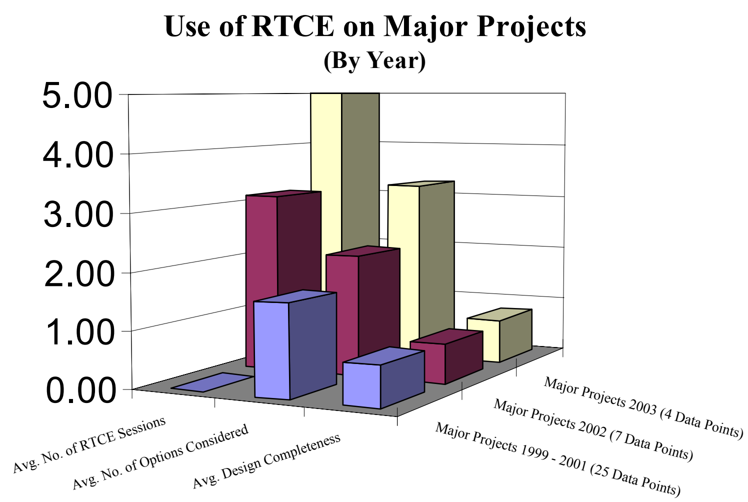
	Avg. Total Cost Index	Avg. Total Cost per Option	Avg. Total Cost per Completeness
Major Projects - Point Design (21 Data Points)	0.25	0.25	0.51
Major Projects - Multiple Options (15 Data Points)	0.35	0.12	0.33

Figure 4-E-4: Cost of RTCE Projects – Comparison of the average Index Cost, the average Cost per Option and the average Cost per Completeness between Major projects that examined only one design option (a point design) and projects that explored multiple options

Number of Options

Figures 4-E-3 and 4-E-4 compare the performance of teams that followed the "point-design paradigm" identified in Chapter 1 with those that took the extra time to examine multiple design options. Design teams that aggressively pursued more options in order to provide their customers with additional perspective or higher quality choices, were able to more than triple the number of options they were able to examine in detail while increasing their costs by an average of 40 percent. This non-linear efficiency gain shows the power of working together in real time.

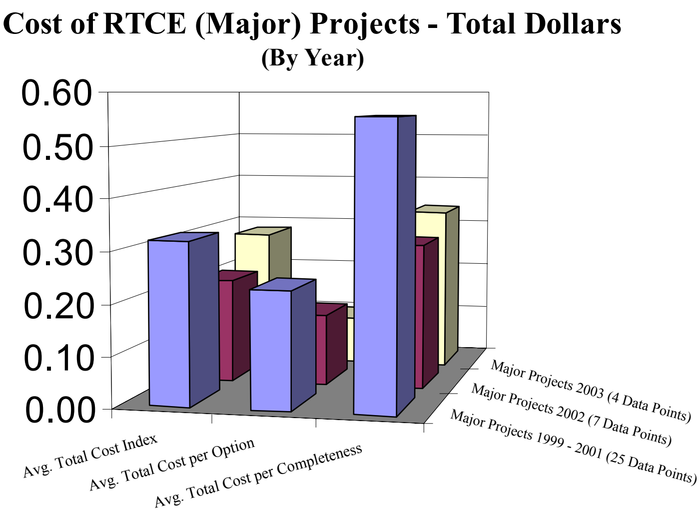
Project Metrics by Date



	Avg. No. of RTCE Sessions	Avg. No. of Options Considered	Avg. Design Completeness
Major Projects 1999 - 2001 (25 Data Points)	0.00	1.60	0.71
Major Projects 2002 (7 Data Points)	3.14	2.14	0.70
Major Projects 2003 (4 Data Points)	5.00	3.25	0.79

Figure 4-E-5: Use of RTCE on Major Projects – Comparison of the average number of Design Sessions, the average number of Design Options considered and the average Design Completeness Index for Major projects completed in 1999-2001, 2002, and 2003

As the skills and acceptance of the RTCE team grew, so too did the average number of design sessions each project utilized. Figure 4-E-5 shows the increasing use of the RTCE process on Major Projects over time. As the team's efficiency grew and project managers began to understand the power of the new process, the average number of options considered by each project team increased. Additionally, as the RTCE process came through development and into full-scale implementation, the average completeness index of each new project climbed.



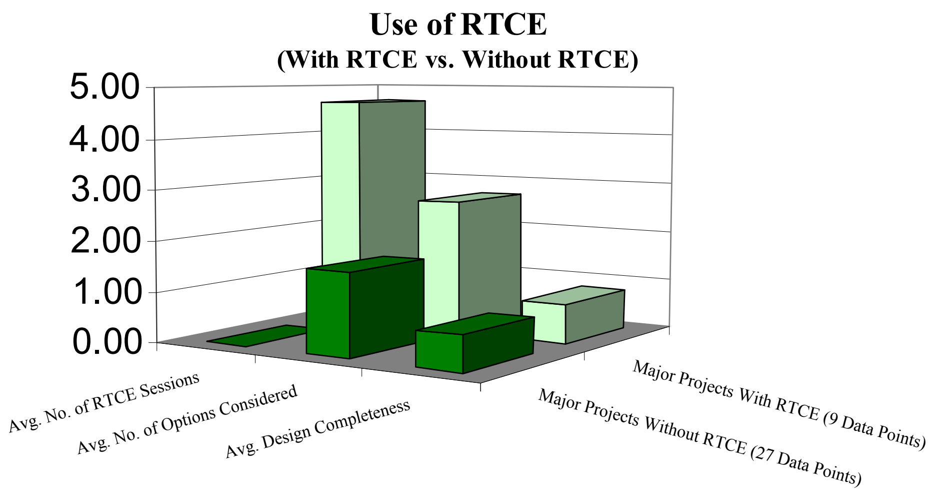
	Avg. Total Cost Index	Avg. Total Cost per Option	Avg. Total Cost per Completeness
Major Projects 1999 - 2001 (25 Data Points)	0.32	0.23	0.56
Major Projects 2002 (7 Data Points)	0.21	0.14	0.29
Major Projects 2003 (4 Data Points)	0.28	0.10	0.34

Figure 4-E-6: Cost of RTCE Projects – Comparison of the average Index Cost, the average Cost per Option and the average Cost per Completeness for Major projects completed in 1999-2001, 2002, and 2003

In terms of efficiency, Figure 4-E-6 shows that some of the gains made by the RTCE team have been slightly eroded in 2003. However, the new product development group is still performing better than it was in the 1999-2001 time frame. These data clearly show reductions in the average cost of each project, the cost per design option, and the cost per completeness index. These trends validate all of the effort that the RTCE team has contributed despite numerous structural, cultural, leadership and financial roadblocks. If these issues were to be adequately addressed, the results would be even more dramatic.

The fact that the 2003 projects were slightly more expensive and less efficient than in 2002 is in line with the observations noted at the beginning of Section 4-D. There, it was stated that many of the new improvements made possible by the RTCE process were partially masked by the market and organizational pressures that surrounded the team. Team members used additional time during the design process to do extra analysis in order to improve the quality of the proposed designs and in order to keep busy as their workload tapered off.

RTCE Use



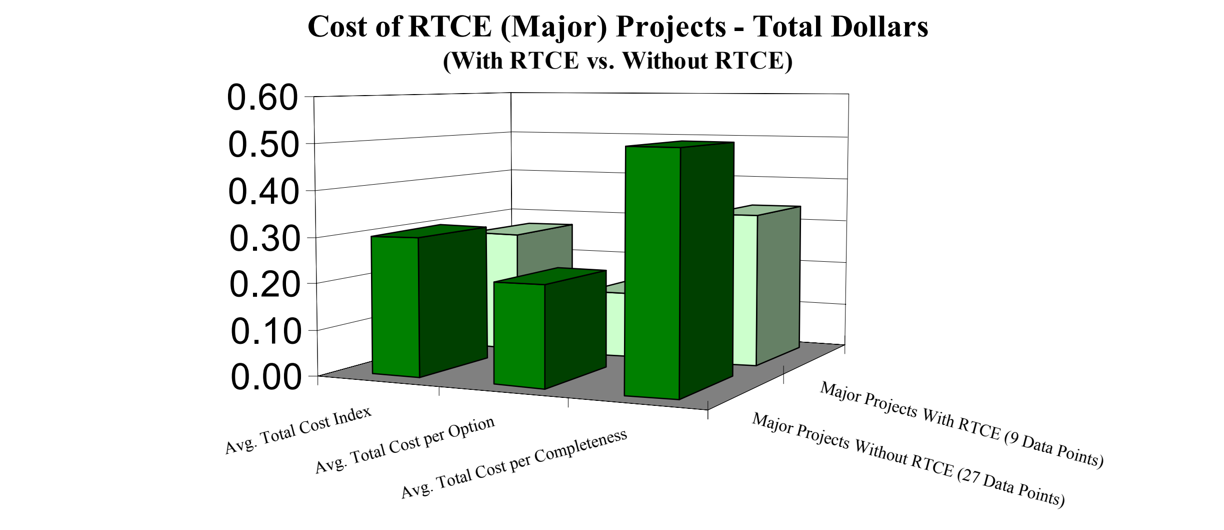
	Avg. No. of RTCE Sessions	Avg. No. of Options Considered	Avg. Design Completeness
Major Projects Without RTCE (27 Data Points)	0.00	1.63	0.68
Major Projects With RTCE (9 Data Points)	4.67	2.67	0.78

Figure 4-E-7: RTCE Use – Comparison of the average number of Design Sessions, the average number of Design Options considered and the average Design Completeness Index for Major projects that used or did not use the RTCE Process

As shown in Figure 4-E-7, project teams have clearly taken advantage of the power of the new RTCE process. On average, they now examine more design options per project, and also work on each one in greater detail.

As Figure 4-E-8 identifies, since the average total cost of a Major Project has been kept about the same, the RTCE process is clearly more efficient than the traditional method as measured by the cost per option and cost per completeness index metrics.

In the case of the RTCE team, all projects have due dates that are set by the needs of the customers, and the average length of a project has not changed much over the past few years. The efficiency gains noted above now mean that the team can accomplish more within the same time frames they have always been given. Instead of using the time to examine one design option in great detail, teams can now look at a few designs during the same time frame and actually go into more detail on each.



	Avg. Total Cost Index	Avg. Total Cost per Option	Avg. Total Cost per Completeness
Major Projects Without RTCE (27 Data Points)	0.30	0.22	0.50
Major Projects With RTCE (9 Data Points)	0.27	0.15	0.34

Figure 4-E-8: RTCE Use – Comparison of the average Index Cost, the average Cost per Option and the average Cost per Completeness for Major projects that used or did not use the RTCE Process

As the RTCE process becomes more mature, the team members more confident, and the project managers more comfortable, the team expects costs per project to decrease steadily over the next few years. New projects are being planned more deliberately, and holding to more fiscal discipline. Whereas in the past, the team just worked as hard as they could to complete a given proposal by the specified due date, the RTCE team now offers a standard "menu" of tasks with predictable prices and lead times. Based on the available budget for any given project, the project manager and the RTCE team can negotiate in advance a list of specific tasks or a level of design Completeness that will be achieved. Later on during a project, items can be either added or removed according to the specifics of a situation without complaints of budget-overruns or team under-performance.

Eventually, as these projects move into the detailed design and production phases, the RTCE team believes that the increased completeness they were able to examine will result in reduced cost and risk throughout the product lifecycle. Using RTCE, they are able to uncover and solve problems early in the conceptual design phase that may not otherwise show up until much later.

Staffing

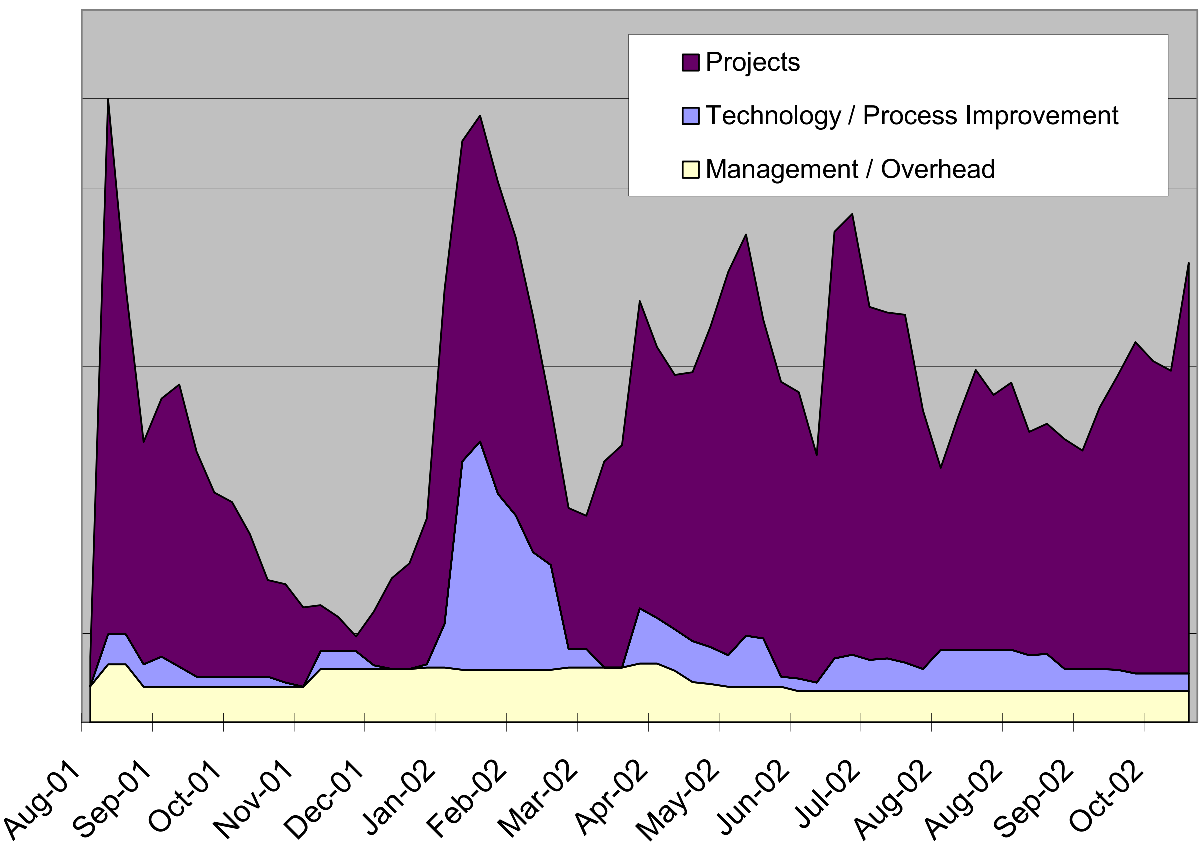
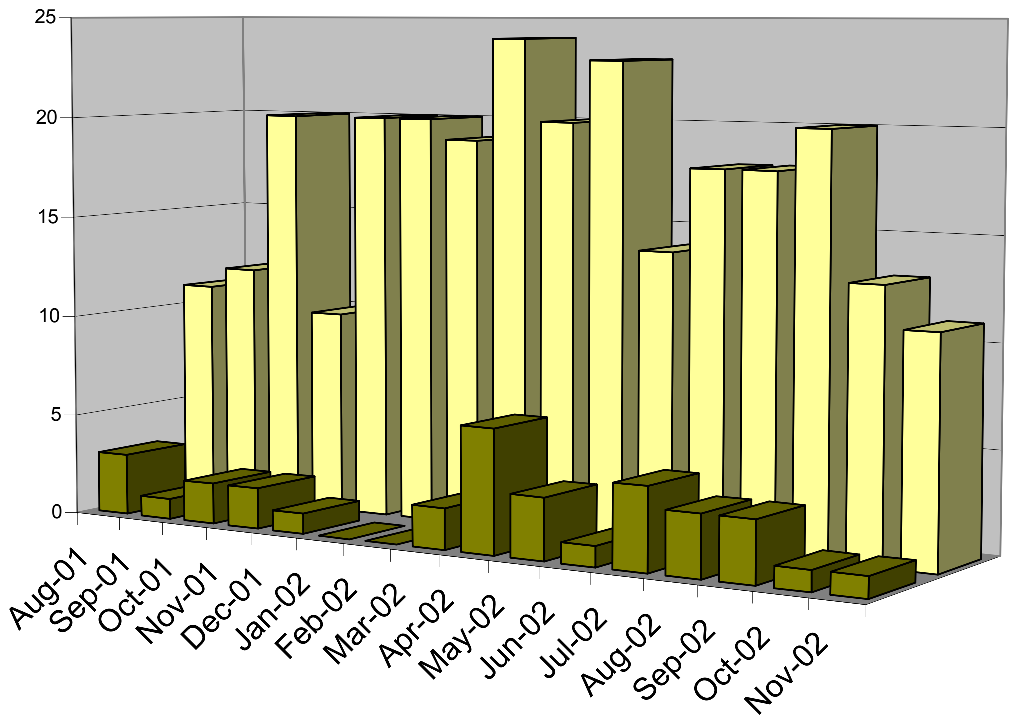


Figure 4-E-9: Staffing – "Equivalent Headcount" (number of 40-hour-weeks billled each calendar week) of projects originating in the Product Development Group of the RTCE Team's company. Hours charged were grouped into categories by the nature of work performed.

Figure 4-E-9 shows the total relative staffing levels, or “equivalent personnel” in the Product Development group (the home department of the RTCE process team). The source of the data is the company’s time card database, which records the hours charged by each person to each task. In order to protect proprietary data, the units have been removed from the graph. The most important observation is the highly cyclical nature of the volume of work performed by this department. Much of this pattern is driven by the demands of the company’s customers. The initial development and validation of the RTCE process accounts for the large spike in the “technology / process improvement” category between January and March 2002 and the increased level of “management / overhead” spending between November of 2001 and April of 2002.

When projects are under deadline, team members often work 50 or 60 hours a week (a rate of 1.25 to 1.5 “equivalent personnel” on the graph above). Additionally, specialists may be brought in from other functional groups to assist on large projects. Likewise, when there are fewer proposals due, the staff of the product development group often fills their time by working for their individual functional managers – charges that would show up in a separate projects category from the one shown above. This arrangement can cause prioritization problems however. If a team member has committed to a project for his functional manager during a lull and an unexpected proposal project arises, scheduling conflicts cannot be avoided.

Figure 4-E-10above shows the total number of Major and Minor projects completed by the product development group. The projects that utilized the RTCE process are a subset of these projects.

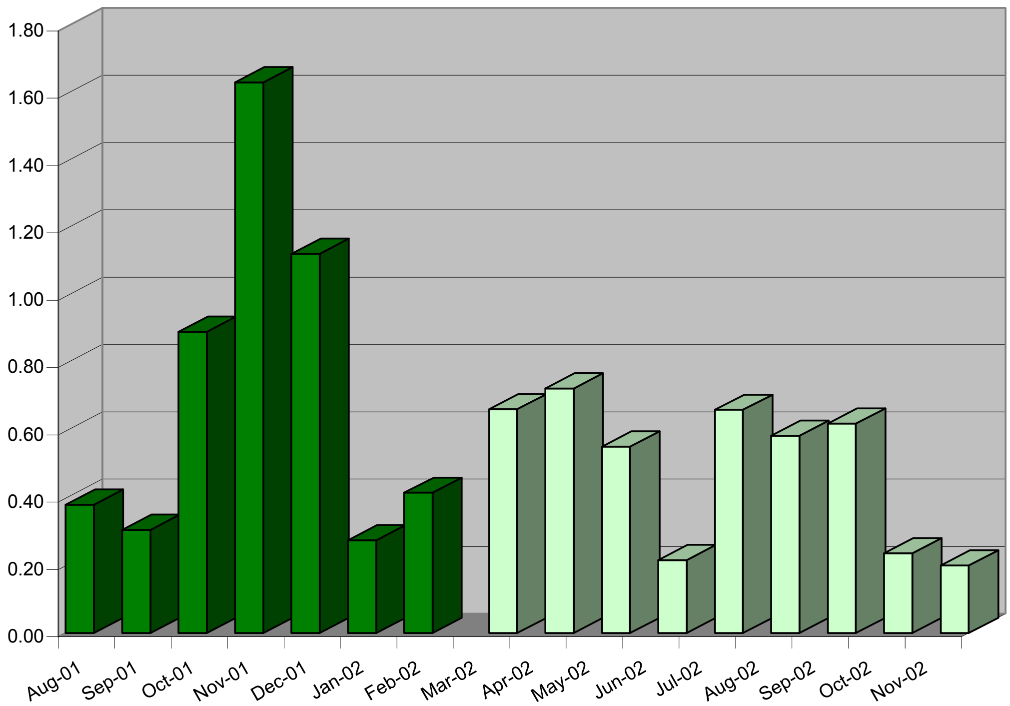


	A-01	S-01	O-01	N-01	D-01	J-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02
Major Projects	3	1	2	2	1	0	0	2	6	3	1	4	3	3	1	1
Minor Projects	11	12	20	10	20	20	19	24	20	23	14	18	18	20	13	11

Figure 4-E-10: Work Load – The number of projects completed by the Product Development Group of the RTCE Team's company, grouped by the month each was completed.

Finally, as defined in the table at the beginning of this section, the Figure above shows the relative productivity of the product development group before and after the implementation of RTCE. The average score prior to the implementation was 0.72, and afterwards was 0.50. These data indicate that, on average, after the RTCE process was implemented, productivity actually decreased, however there may be more than one explanation for this observation.

The most important driver of this difference was the extremely low level of staff hours charged between October and December of 2001. During this time, the author may have been unable to obtain complete data, or an accounting error occurred – some of the projects "completed" during those months may have been in-process for quite some time and thus the hours charged were not properly matched to the time frame that the project was booked as complete.



	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02
Without RTCE	0.38	0.31	0.89	1.64	1.13	0.28	0.42									
With RTCE								0.66	0.73	0.55	0.22	0.66	0.59	0.62	0.24	0.20

Figure 4-E-11: "Productivity" of the Product Development Group of the RTCE Team's company. This metric is a generalized measure of the value-added work being accomplished within the department. It is calculated by taking the total number of project units for each month and dividing by the average total staff level that charged their time to the "project" category in Figure 4-E-10.

Next, the time period represented by the data may not long enough to show the actual trend. The initial months of RTCE implementation were a time of learning and experimentation – the team took their time to build a robust tool and often encountered setbacks. In the long run, the leadership of the RTCE team was confident that the productivity metric would show positive improvements.

However, as explained previously, the productivity, or Return on Investment, metric should not be the overarching measure of the success of the RTCE team. The increased quality, speed, accuracy, innovation and learning opportunities provided by the RTCE process will have profound benefits on the entire product lifecycle resulting in products that deliver more value to customers and present less technical and financial risk to the company.

Summary of RTCE Team Metrics

On average, in their first year RTCE projects cost 10% less than traditional projects. Although this was not the radical savings the team leaders had initially hoped for, the team firmly believes that their costs will drop steadily as they continue to learn and improve their process. It is still too early to calculate a traditional return on investment (ROI) metric for the savings generated by the RTCE process. However, the investment did purchase the following:

- On average, using RTCE, each new product design project was able to consider 64 percent more design options.
- Each option is examined to 15 percent more detail.
- As measured by both the cost per option and cost per completeness metrics, the RTCE team was 32 percent more productive than they had previously been.

As the first few projects that used the RTCE process move into production over the next two years, the team is completely confident that the data will reveal that their ability to examine more designs in greater detail early in the conceptual design process will result in production programs that yield higher quality products that can be repeatedly manufactured on-time and on-budget.

Section 4-F: Deep Dive: Implementation of MATE-CON

During the summer of 2002, the addition of a trade-tool capability was proposed to the RTCE team leadership. The concept was intended to enable the RTCE team to perform the following functions:

- Capture and prioritize customer preferences
- Target regions of the potential design-space for closer examination

- Objectively compare one proposed design to another
- Easily and objectively compare a proposed new design to past products the company had successfully produced
- Keep track of small iterations off of a proposed design, and evaluate if each was better or worse than the baseline
- Evaluate a proposed design versus the best estimates of what know competitors would offer to the customer
- Communicate in one visual graphic to managers and customers:
- Communicate why a proposed design was chosen
- Communicate how proposed designs were evaluated
- Analyze and communicate the strengths and weaknesses of proposed designs, and determine how much it would cost in terms of time and money to eliminate each of the weaknesses

The MATE-CON process described in Chapter 3 was proposed as a method of providing the above functions to the RTCE team. Unfortunately, the process has still not been implemented due to a number of technical and cultural issues.

One team leader in particular was extremely enthusiastic about the use of MATE-CON. Almost immediately after it was proposed, however, he struggled to find appropriate attributes of the systems that the team designed. In particular, the team typically had three of four high-level requirements that could easily be turned into attributes – the trade-offs between these were already well understood, however. The real need arose when the team traded off second-tier requirements, of which there were typically between 20 and 40. Since the current MATE-CON process can only accommodate up to seven attributes simultaneously, this situation presented a problem to the implementation leader. A number of creative groupings were proposed, but in dong so, the team would lose the ability to actually trade between the different parameters. Additionally, going through the MATE-CON utility interview for a large number of attributes was time and reason-prohibitive. It was just too difficult to estimate the value of certain hypothetical systems, and the probability of success of each proposal.

Second, the team had a large disconnect between their design process and their potential customers. The nature of the industry they were in was heavily dependent on a competitive bidding process that prevented open communication between the company and a customer during the proposal process. Typically, one senior manager was assigned as the company's representative to the customer. MATE-CON was presented to several of them, but not one ever requested additional information or a more detailed explanation. Most thought it was too complicated and completely unnecessary. The customer representatives believed that they provided all the information that the design team could possibly need. This was untrue in a few cases, although most of the customer representatives did not attend the concurrent design sessions or left "after their part was done." This frustrated the design team because they often had to make difficult choices based solely on their own guesses about what a customer might want, or were forced to do two or three complete designs in order to have the representative choose one that might be presented to the customer.

Third, in order to compare new proposals to existing designs using MATE-CON, the team needed to access to historical data for all of the chosen attributes. The data were utterly unavailable to any team member. No centralized data storehouse was maintained, and most project managers kept their own files according to what they thought was important, often leaving large pieces of information incomplete when they transferred to other divisions, left the company, or were laid off. An extensive search of all available records was undertaken (totaling more than a month of the author's time), but not enough information was located to complete the project.

Finally, even if the team had wanted to implement the new process, the RTCE team was not given the time or resources to develop a stand-alone MATE-CON tool that could be integrated into a design session, nor did they have the ability to assign a team member to operate it during a session. This, and the database project mentioned above, were not the only areas of potential improvement that were picked up, then neglected again and again by team members who volunteered to try them out in their free time but simply did not have enough time or motivation to see them through.

The following is a summary of the lessons learned when the RTCE team attempted to implement the MATE-CON process:

- True customer collaboration is essential – this requires cooperation between designers, managers, sales and marketing people, and the customers themselves.
- Trying to implement a new system is a risk, and many people will be afraid to try new ideas because they are threatened by them.
- Defining MATE-CON Attributes is labor intensive and requires skill and patience
- The Utility Interview (which determines the utility curves used in a MATE-CON analysis) is difficult and elicits the voice of only one key decision-maker at a time
- Modeling the system at an appropriate level of detail takes discipline and coordination
- Parametric Models are difficult to construct
- Need to incorporate error-checking and limits with closed form solutions in the models
- Challenge: How to model systems that have never been tried before
- Cost Models can be very influential
- The basis for the models will drive your design – make sure you agree with the underlying assumptions
- If you base new costs on historical costs, you may never achieve new innovations
- MATE-CON is intended to be an iterative process
- Users should maintain an open line of communication with key decision-makers and validate output continuously
- Don't waste time in the beginning trying to make perfect models
- Go for a uniform accuracy target (+/- 5%) at first, then hone in on the important areas of the tradespace and improve your models

Section 4-G: Strategies for Near Term Re-Vitalization of the RTCE Team

As is the case at most aerospace companies, when it comes to project implementations, the strong engineering heritage of the company guides the organization along the most comfortable path: technology. Engineers – and managers who were once engineers – are fantastic problem solvers. When faced with the challenges listed above, the RTCE team reacted in the way they were trained and rewarded for acting throughout their careers – by proposing and implementing strong technical solutions to the most tangible problems, and leaving the rest for another day.

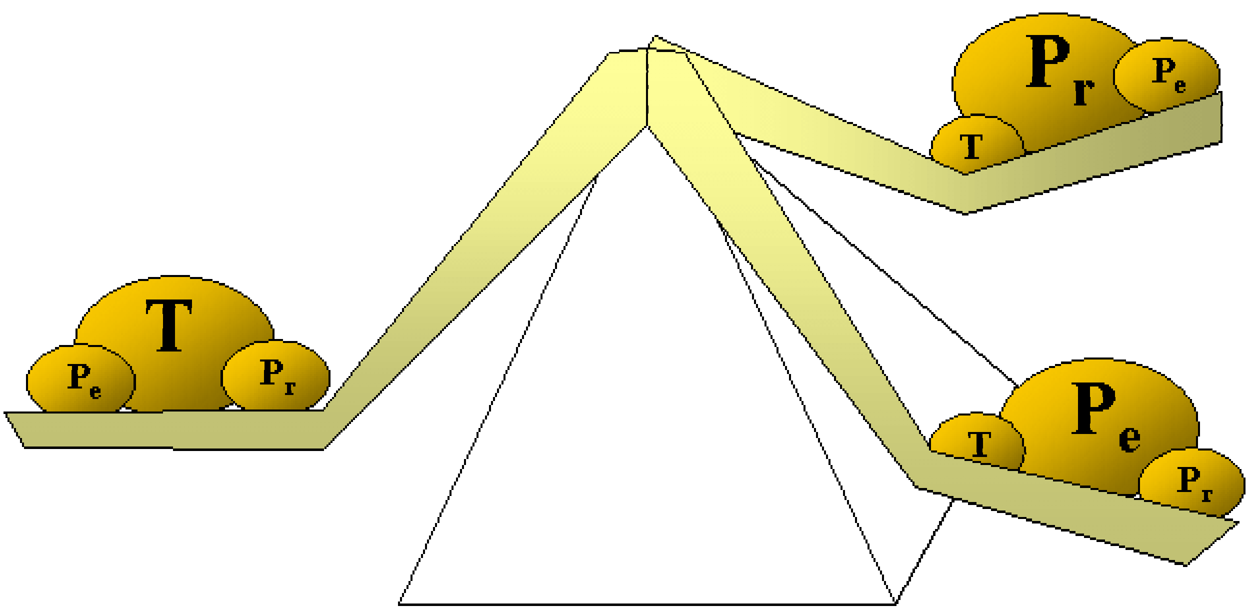


Figure 4-G-1: The "TPP" Model shows the interaction of the "Technology (T)," "People (Pe)," and "Process (Pr)" issues that dominate any project implementation. All three areas must be addressed in proportion in order to achieve process harmony. Actions taken in each category help the efforts in other categories to become more effective.

Through observation and collaboration, the author is proposing a new model through which the positive achievements and the potentially damaging issues delineated in the previous sections can be highlighted and addressed. Figure 4-G-1 shows a pictorial representation of the careful balance that must be struck between Technology, People and Process in order for any project to be successfully implemented. A similar framework was proposed by (Neff and Presley, 2000), after the implementation of a similar team at the Aerospace Corporation As the RTCE team learned first hand, regardless of the potential value that a new innovation can create, the implementation team must examine and solve problems in all three categories. If a team focuses disproportionately on the technical challenges, the project will encounter people and process issues that will impair their progress or negate the value they have created.

Technology: In the span of approximately 9 months, the RTCE team transformed the ICE concept into a working reality. The team can now design low to medium NRE (non-recurring engineering) products in approx 4 to 12 hours compared to 2 to 4 weeks using their previous approach. Nineteen subsystem clients (ICE functional analysis tools) were written and technically validated. Over 7200 universal design variables were created, assigned and made accessible to every team member. A robust data management system was created and implemented. Automatic documentation tools – an idea initiated by team members as a process improvement – were added to each client.

In the next year, the team has several tasks that need to be accomplished in order to address some of the technical issues highlighted in the previous section. First, a sub-team must meet with representatives from the operations division in order to integrate their expertise into the real-time concurrent design sessions. New clients must be created as appropriate in order to provide the RTCE team with more accurate cost, lead-time and schedule information. Other ICE teams at JPL, Caltech and MIT employ 3-D visualization techniques so that designers can use their intuition to better understand how their subsystems will come together to form a high-performance machine. The RTCE should first implement a very low-cost, high-level tool such as Drawcraft which links the designer's excel spreadsheet to SolidWorks®, a solid modeling tool (Liu, 2000). Once the team explores the benefits and difficulties of this new capability, they can then deploy a complex tool such as Pro-E®. The RTCE team must find a way to integrate historical data for comparison purposes. Finally, they must implement a rigorous and objective group decision-making methodology, such as MIT's MATE-CON process, in order to explore the product architectures they create with respect to their customer's stated values (Diller, 2002).

People: The original RTCE team kicked off the project with a high level of enthusiasm and energy. They were excited about a new way of doing business and knew that their leadership had committed significant resources to the success of the project (i.e. the entire overhead budget for the next year).

As discovered in the previous section, however, human issues slowed the team's progress and created conflicting messages. The RTCE project should be staffed with full-time dedicated personnel (Browning, 1996) and (Klein and Susman, 1995). This standing team will avoid conflicts of time, energy or loyalty and promote process improvement at an accelerated pace (Pomponi, 1998) (however, the modular structure of the RTCE process allows for subject-matter experts to be added as necessary, and for on-the-job training of new team members). It should consist of people from all functional and business departments – especially from marketing and operations. Team members should be chosen on the basis of their energy, cooperative spirit, innovativeness and system-level perspective as well as technical competence. There should be a healthy mix of "knowers" and "learners." The experienced seniors can help guide the team towards designs that will be less expensive to manufacture and that avoid failures that have taken place in the past, while the younger team members can help provide the real time, analytical horse-power the team will need to carry out its mission.

These team members should come together to establish common values and work norms. The leadership should effectively communicate their expectations to the team, and should explicitly evaluate and reward individuals and the team when expectations are met. The team should also create a forum for the training of new team members as well as an opportunity for others in the company to visit and learn about their process. Ergonomically, the team leaders should ensure that the team's homeroom is clean and quiet, that the temperature is comfortable and that all team members' human needs are tended to so that people can perform at their maximum potential.

Process: There are a number of key process achievements that the RTCE team was responsible for. They successfully integrated RTCE into the company's new proposal process. At this time, all new business opportunities utilize this innovative new technique. The team developed session scripting which enables people to understand the current focus of the design session, to facilitate information sharing and to keep the session flowing smoothly. The use of the "around-the-room" method allows each team member to share their input and have visibility to underlying assumptions and problem areas.

To complete the TPP analysis, the RTCE team should continue to focus on process improvement. They must create a feedback mechanism so that team members can voice opinions and implement their own process improvement ideas rather than leaving that burden exclusively to the team leadership. Metrics and goals should be posted and evaluated daily with a focus on continuous improvement. The team must avoid sub-optimization by encouraging system-level solutions even if one or two subsystems are less efficient than they would otherwise be. During the design sessions, two leaders are required to focus on different aspects of the process so that each team member can be free from administrative burdens. Having one leader who focuses on the technical aspects of the system and another that deals only with the smooth flow of the process will enable the team to operate at their maximum efficiency and have time to think innovatively.

The author also provided a roadmap for the integration of RTCE processes and concepts into the other phases of product design, manufacturing and test (Refer to Section B of Chapter 6). In the first phase of this effort, the RTCE team would enhance their current capabilities as described in the previous paragraphs. In Figure 4-G-2, the round circles that surround the ICE homeroom graphic indicate these additional team resources. Each circle could represent subsystem experts, additional team members, databases, or even small teams of suppliers or others who are available to assist the RTCE team during a design session.

Next, the team would build a "negotiation tool" that would help them rapidly provide detailed technical and financial updates to the negotiation team that is typically sent to finalize and sign a contract with each new customer. During the course of these negotiations (which typically occur in the offices of the customer), the negotiation team is often asked to sign up for increased performance or lower costs than initially offered in their written proposal. Using this new "ICE-on-a-laptop" capability, the team would be able to accurately evaluate the customer's requests and be able to show the customer the impacts or benefits of particular options. The tool they would carry with them to the negotiation session would be a high-level extraction of the full RTCE parametric model. It would have certain "design knobs" that could be tuned, but would also have a series of pre-determined 'limits' that would notify the negotiation team if they need to convene a full RTCE design session back home in order to update the proposal.

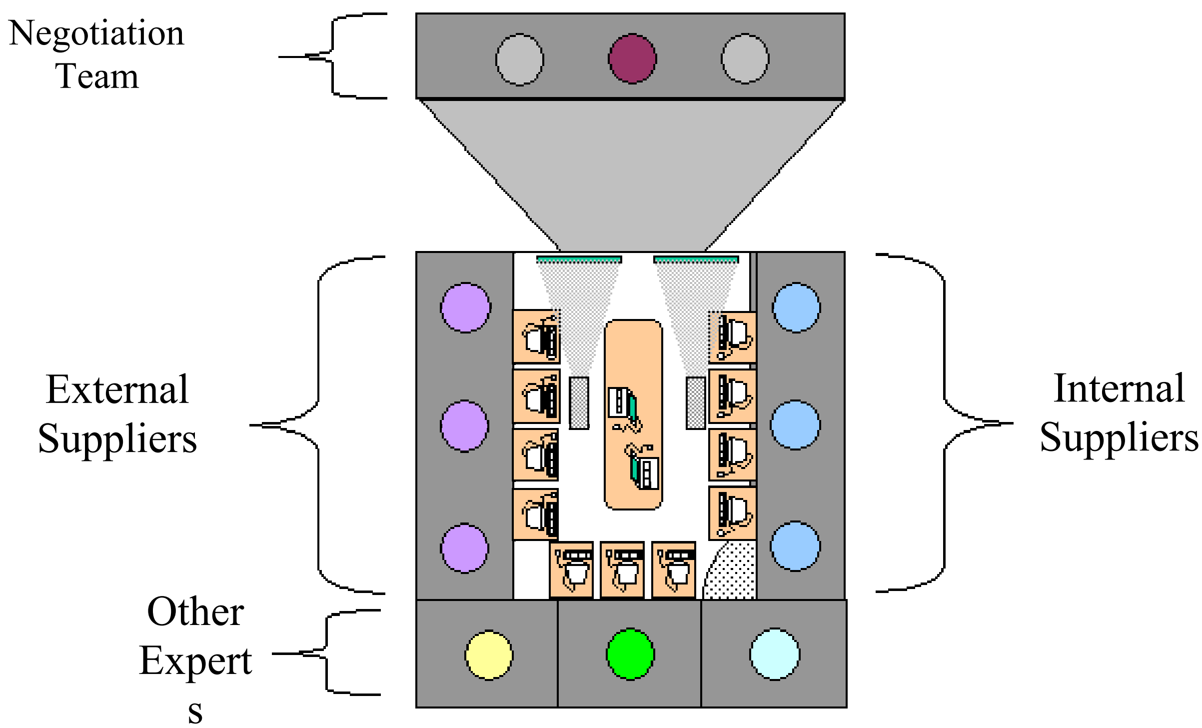


Figure 4-G-2: The off-site Negotiation Team is supported by the primary design team at home who are in turn supported by additional stakeholders and experts.

In the next phase of expansion, the RTCE process and models would become the backbone of all detailed design work that occurs after the company has won a new project. In the current system, the output of the RTCE team is mostly discarded because it is not in the format that can be used by the detailed designers, nor do they trust the analysis that was performed by people they do not know. In the proposed concept, the original RTCE team would gradually hand off ownership of the models and processes as a program comes to life. As more detailed work begins, teams of specialists can be added to support the main RTCE team. So, instead of having one subsystem model, an entire RTCE team could be plugged in to the system. The overall system model would be 'synchronized' on a daily or weekly basis by the main team in order to monitor the progress of the design work. These meetings would highlight new changes or issues that have arisen – designers would still be working with parametric models so they would be able to detect the impact that changes would have on their subsystems, and the project managers would be able to keep the team on schedule and on-budget by pacing the tasks that are to be completed by each update session.

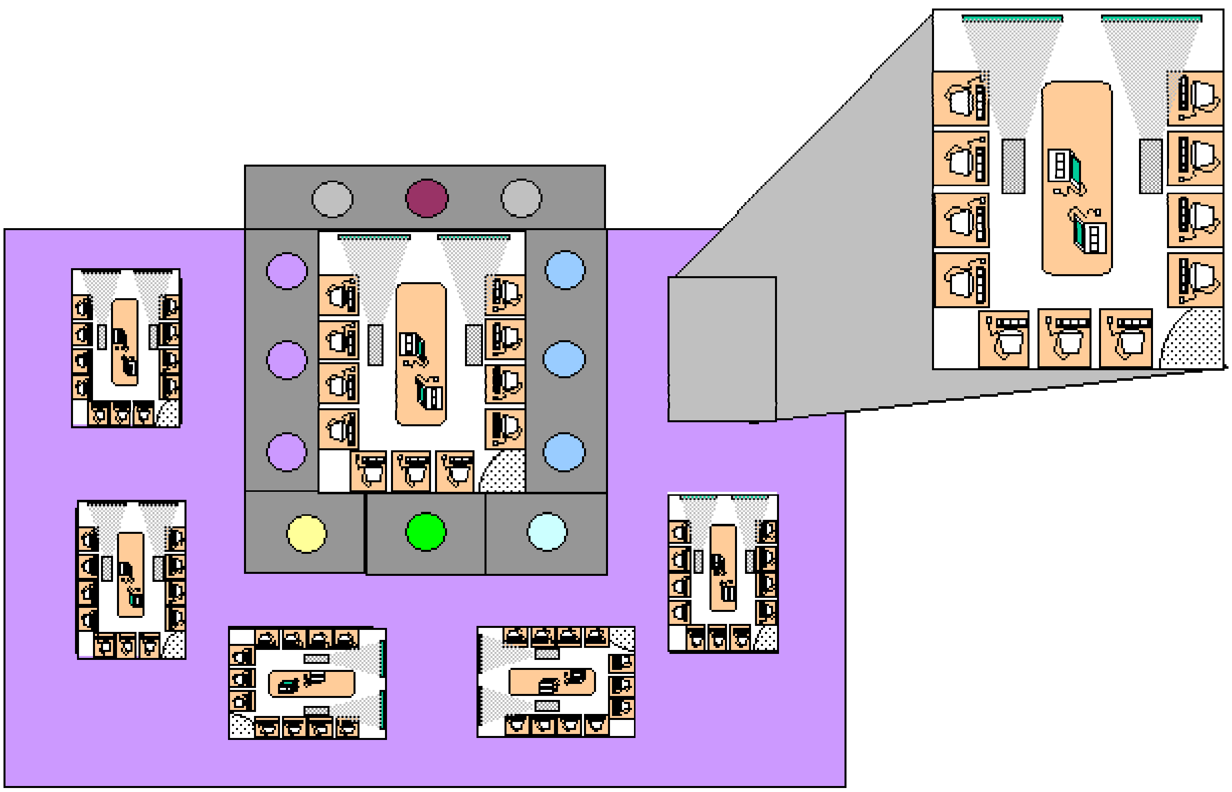


Figure 4-G-3: Other ICE teams are formed to support the primary design team. Their models are linked parametrically to the master product design.

Once the product design is complete and the team is ready to begin fabrication, the RTCE facility and models become valuable tools for monitoring the progress of hardware integration and performance with respect to the predicted values. If particular subsystems do not perform as specified, the models can help the team quickly assess the potential impact of the discrepancy and determine an accurate disposition. The system would also help the team perform and document complex system tests. Optimally, the manufacturing facility would be directly adjacent to the team homeroom so that the entire team can coordinate their activities and again see the impacts of their decisions in real time.

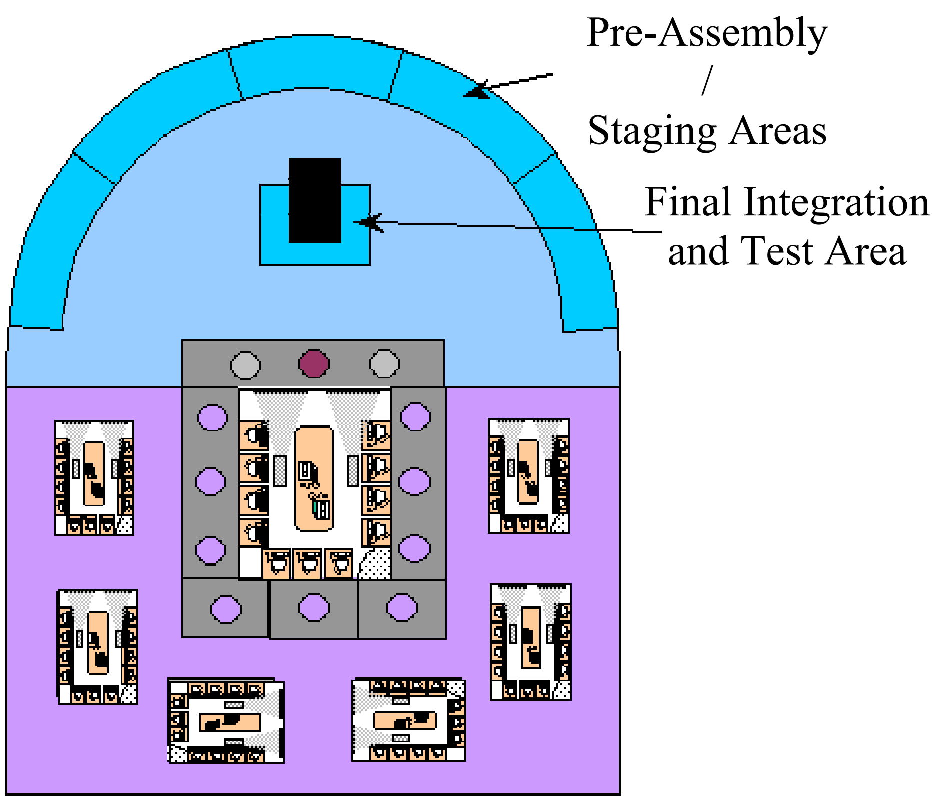


Figure 4-G-4: Collocation of Design and Fabrication Facilities for each new ICEnterprise will increase visibility and communication and keep the team focused on the smooth flow of operations in order to ensure on-time delivery.

Section 4-H: Summary of Organizational Implications and Recommendations

Summary of Organizational Implications:

- The nature of the company's organizational structure created barriers between the RTCE team, and the critical people and information they needed.

- Managers of other divisions within the company did not see the potential positive impact that RTCE could have on the company as a whole. This lack of buy-in manifested itself in the form of minimal support that detracted from the potential gains the team could make.

- The company's senior management team did not adequately understand the vision for the RTCE project. This was partly due to their focus on short-term profitability and partly because the RTCE leadership was unable to articulate a cohesive message to the proper audience.

- RTCE participants were thrust into entirely new types of jobs, and their training, motivation and incentives were not yet properly aligned with their new responsibilities.

- Managers in peer departments judged the project based on second-hand information and with respect to their own personal agendas.

- The RTCE leadership team faced difficult personnel and management issues yet lacked the authority or the mandate to make tough decisions and push team members to make changes outside of their comfort zones.

- Rather than enabling positive change, the company's accounting system prevented well-intentioned people from spending their time on work that would help make the company more profitable in the future.

Author's Conclusions on the RTCE team:

The real-time concurrent engineering team has created a jeweled "island of success" within their company (Murman, 2002). The team successfully brought about change during a complex and uncertain period of time. They applied innovative solutions to emerging technology, personnel and process challenges. The team worked passionately from their initial positions and reached out beyond the safe boundaries of their existing job descriptions. The organization around them responded defensively – the company had reached its current size and market dominance by forming a strong culture that resisted change. It gained efficiency through standardization, training and institutionalization – its customers paid for absolute predictability and reliability, not for unproven experiments, and the employees behaved accordingly.

The RTCE team leaders have successfully pushed beyond the boundaries of their home department. If the company is ever going to realize the tremendous technical and strategic value that the real-time concurrent engineering process can provide, the project must be supported and nurtured at the highest levels of the organization. The President must lay out a clear vision and follow through on a methodical expansion of the scope and impact of RTCE. The senior leadership should choose the most important attributes of this new business system – namely the continuity and universal accessibility of design information - and instill these as core values throughout the company. Next, the senior leadership should avoid the temptation to freeze and standardize the process as done with specific technical tools. Rather, they must foster an air of excitement and invention. They should clearly articulate the problems that the company is facing, and then describe in detail how a new approach that links all the key functions of the company in a manner never before possible, will provide a path toward sustainable success. There will be many new challenges along this path, but an approach that balances the technical, people and process issues will ultimately lead to long term, enterprise-wide value creation.

Chapter 5: The Integrated Concurrent Enterprise – Vision

The RTCE case study revealed a number of organizational barriers that are preventing an ICE team from revolutionizing the way people work together throughout the company in question. The ICE paradigm does conflict with an organization built specifically to support the decomposition method. Thus a completely new type of business model needs to be built – from the ground up – if practitioners are ever to release themselves from the traditional constraints of sub-optimized designs and organizations.

Section 5-A: Review of Findings

Organizations have traditionally battled the onslaught of complexity by decomposing problems into small pieces. While this approach creates interchangeable job descriptions and easily defined tasks, it leads to either highly complex (and expensive) management structures or sub-optimized system designs.

Numerous business processes have been introduced to minimize complexity and streamline organizations and information. Information technologies have allowed individual designers to be more productive and thus minimize the number of decomposed tasks. Leaders have worked hard to create a higher level of awareness for all the people on a given project team and to break down traditional organizational barriers. As a shining representative of these new techniques, the RTCE team employed the concept of Integrated Concurrent Engineering to dramatically improve the quality and speed of the design process and to promote innovation and learning.

As measured theoretically (by the Parallelization, Standardization and Integration criteria) and practically (by repetitively successful implementations) no single approach discussed above brings a satisfactory resolution to the challenges identified. Despite their initial successes, even the RTCE team failed to strike a balance between the Technology, People and Process elements that must be systematically identified and managed in order to create and sustain excellence in any complex undertaking. The structure of their corporation – the financial, organizational and human resource processes that are applied uniformly and rigidly across every single project – and the beliefs and tactics of the current managers has stalled the RTCE team just short of an enterprise-wide breakthrough.

The next great giants of enterprise will not find radical success by simply improving upon the methods of Henry Ford. Instead, the very nature of the corporation must be re-thought and re-born.

Section 5-B: Guiding Principles of an ICEnterprise

Based on the above findings, the author is proposing a new type of organization, with the following definition:

> An "Integrated Concurrent Enterprise" (ICEnterprise) is an organization in which the flows of people, products and information are seamless, visible, reliable and agile. This new organization will not only harness new ways of working together and sharing information, but will also break the paradigms set by traditional corporations and industries. Large organizations begin with a bloated cost structure and large bureaucracies. They then try to become Lean by implementing best practices across the board and outsourcing labor and material. An ICEnterprise, in contrast, will begin with no formal structure or assets, and will then in-source everything it needs to complete a specific project.

The author further proposes that any team, company or industry can create and sustain tremendous value by transforming itself into an "Integrated, Concurrent Enterprise."

In this context it should be noted that the definition of "value" is expanded to include more than just profit and is different for each stakeholder (Murman et al, 2002). Depending on the nature of the relationship between two partners in an agreement – and on the context of the product or process being delivered – value may be derived in the form of speed, reliability, redundancy, flexibility, reputation, job security or many other alternatives.

(AIAA, 1991) identified ten characteristics of highly successful system design projects that are directly applicable to an ICEnterprise. The leadership of any new venture should incorporate these principles into the design and continuous improvement of their new organization:

1. "Comprehensive Systems Engineering Process Using Top-Down Design Approach
2. Strong Interface with Customer
3. Multi-Function Systems Engineering and Design Teams
4. Continuity of the Teams
5. Practical Engineering Optimization of Product & Process Characteristics
6. Design Benchmarking Through Creation of a Digital Product Model
7. Simulation of Product Performance and Manufacturing Process
8. Experiments to Confirm / Change High Risk Predictions
9. Early Involvement of Subcontractors/Vendors
10. Corporate Focus on Continuous Improvement & Lessons Learned"

Section 5-C: Organizational and Cultural Attributes / Concept of Operations

The operational model of the Integrated Concurrent Enterprise is based on the system currently employed by Hollywood studios – in the author's opinion, the best example of a virtual, flexible organization that currently exists. While traditional engineering organizations rely on large "standing armies" of engineers and technicians that can be applied to any new project, film studios purchase labor and services only as immediately necessary and pay market prices.

The movie studios that produce major motion pictures consist of a relatively small permanent staff, and rely on a pool of skilled talent and reliable service providers to complete each new film. Although the product produced is clearly of a different nature than the complex engineered products that have been the subject of the prior 4 chapters, the size (approximately $20 to $200 Million per project), scope (total project employment may range from 100 to 2,000 at any time) and duration (projects last six months to three or more years) are similar in nature. Whereas traditional companies have new business departments that continually pursue project opportunities, studios rely on a more entrepreneurial model where hundreds of new ideas for products arrive at their doorstep each day – sent by passionate artists who are willing to enter into high-risk, high-reward contracts in order to prove the validity of their ideas and the unique skills and innovations they possess.

Successful studios retain and manage the organizational knowledge that nearly always ensures successful new ventures. They provide the capital to fund these new initiatives as well as the enabling infrastructure that helps the entrepreneurial stars complete high quality projects in a timely manner by connecting them with proven yet applicable processes, talent and services. The system inspires innovation and a continuous drive for higher performance by allowing stars to retain a great deal of freedom in choosing from the available infrastructure and talent rather than forcing every project into one-size-fits-all "best practices" or by assigning whomever is available (at a fixed price) rather than the best talent available at a market-defined price. The system only works, however, because a "critical mass" of innovation, talent and services exist. If only one studio or one stagnant supply of employees and vendors existed, the current rate of success and improvement would surely cease because the incentives to innovate and compete would vanish accordingly (as they often do in large engineering corporations).

In the current corporate environment, new ideas are often squelched due to internal political or organizational barriers. Star performers are often held back from recognition by seniority systems or traditions, and rewarded nearly the same as poor performers. For example, in most major engineering companies, yearly evaluations result in merit-based bonuses – poor performers may only receive the minimum raise of 1 to 3%, while rising stars within the engineering and management ranks may receive 5 of 6% in a typical scenario. Top salaries for even the best engineers rarely reach double that of their poor-performing peers or new hires without any experience at all. Revenue-sharing concepts do not exist as incentives for individual high-performers – nor do they have the ability to choose projects that they are passionate about or have full decision-making authority in regards to their team members, the processes or vendors they will use to complete a project, or how much each will be paid.

Therefore, the proposed permanent structure of an ICEnterprise would consist of a relatively small full-time staff of highly experienced technical and business leaders. These would be highly successful, proven leaders who have the insight and passion to guide young innovators to great success. The company would retain process knowledge, enabling infrastructure (although each project would rent office space and manufacturing space that is specifically appropriate for each new project), access to capital, and a characteristic personality or reputation. In essence, the ICEnterprise does not function as an all-inclusive organization, but rather as a conduit for great people to achieve great successes.

Figure 5-C-1 presents a general Concept of Operations for an ICEnterprise. Figure 5-C-2 shows the parallel structure of a generic large US corporation. In the first Figure, the ICEnterprise is depicted as an umbrella organization with flexible corporate boundaries (depicted as dashed lines). Each new project follows a "composition" process as opposed to a "decomposition" process in the traditional organization. In the ICEnterprise, a new team is composed from the available pool of talent and suppliers – it is free to grow and work in any way its leadership wants. The project team builds very tightly integrated relationships with its various team members and suppliers because of the highly focused nature of each project. The new team is given expert guidance from the ICEnterprise in addition to the necessary capital and access to its process and technical knowledge base.

In the traditional corporation depicted in figure 5-C-2, a new project enters the company and is decomposed into a number of tasks that are then assigned to existing departments or internal suppliers. If necessary, external suppliers are hired to perform some tasks of provide raw materials. These suppliers are often managed by a purchasing department that insulates them from the project team. They therefore typically do not receive relevant project information and feedback in a timely manner, often causing delays and rework. In general, each new project is forced to fit the existing organization. In contrast, in the ICEnterprise, a miniature organization is built to custom-fit each new project.

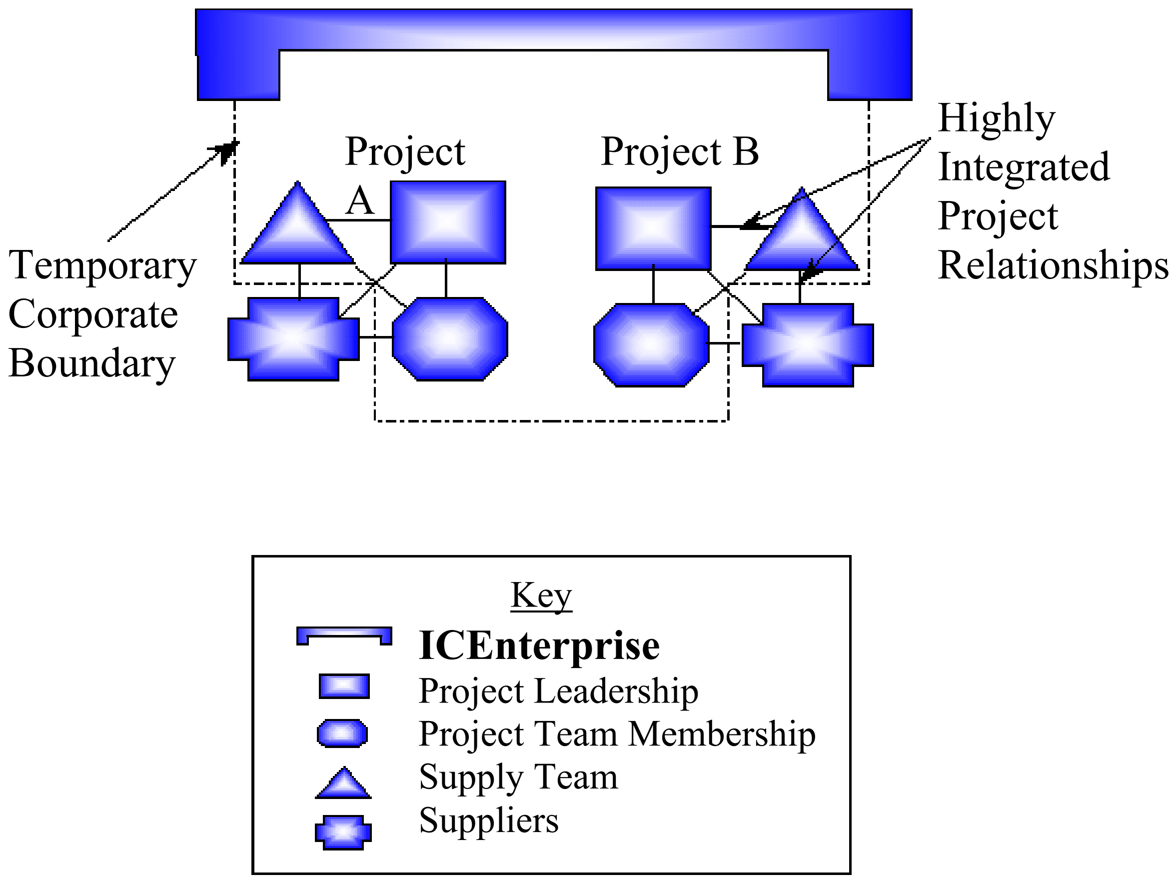


Figure 5-C-1: ICEnterprise Concept of Operations – Highly integrated project relationships are more important than corporate boundaries. The ICEnterprise enables project success but allows the project team to structure itself in the most appropriate manner to complete their tasks.

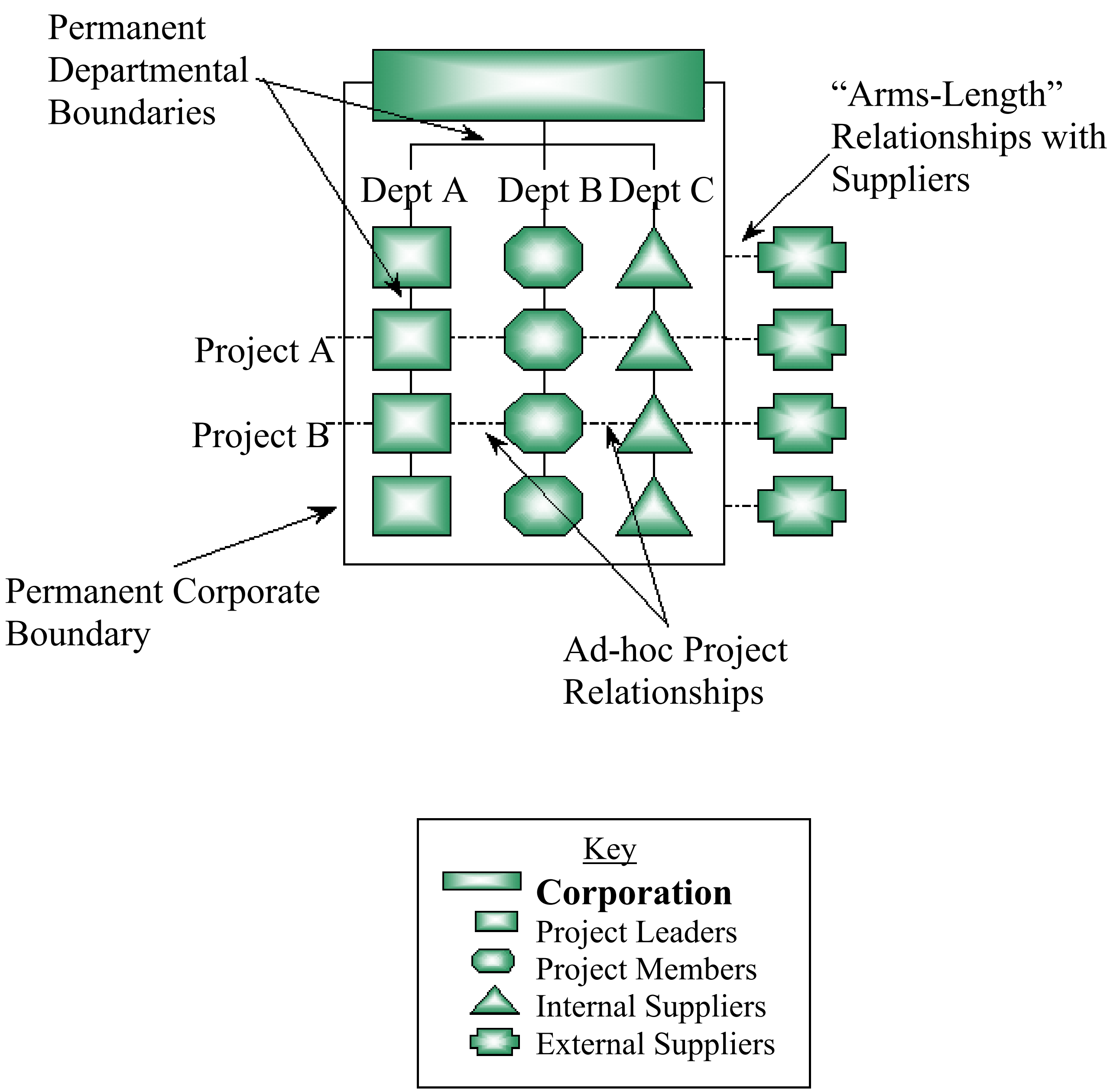


Figure 5-C-2: Traditional Corporation Concept of Operations – Ad-hoc project relationships are constrained by corporate boundaries. Departmental standards help some projects but hinder others. Poor relationships with suppliers increase cost, complexity and lead times.

As with top-ranked studios and stars, an ICEnterprises reputation with its customers for managing its projects well can translate into premium pricing. In many ways, this is a similar principle that is employed very profitably by large consulting firms like McKinsey and Co. Even though they essentially send out highly educated and talented individuals to complete projects, the majority of its consultants have less than ten years of industry experience, and turn over almost every two years. However, McKinsey's clients are willing to pay huge sums for the McKinsey name because they know that the final project quality will be high – the Technology, People and Processes that McKinsey's teams employ ensure a consistent delivery of world-class consulting products. The same principle applies to movie studios – if a well-renowned star or producer is involved, the project can demand premium pricing because the studio and its capital customers have a high degree of confidence that the movie will be a hit, and there is far less risk of the project finishing over-budget or under-delivering in quality.

Hiring Talent: When an innovative and potentially profitable idea is proposed to an ICEnterprise and accepted, the new team leader will immediately begin to hire a star team. Each new team member will be hired on contract for the duration of the project and on a full-time basis. However, each talent contract will contain 25% more time than necessary to perform the task at hand in order to allow the talent pool to develop the skills, processes and technologies that will ensure the long-term sustainability of the ICEnterprise model. Although this "tax" on all work will represent a burden to all projects, it will be agreed upon as an industry standard, and even though it does not represent all costs associated with a team member (such as office space, computers, etc) the comparable rate in current engineering corporations (in addition to the salary paid) can be 200 or even 300% of the actual compensation paid to an employee. Vacation time is negotiated into each contract, as is sick time.

The 25% "enterprise capability development time" will be broken down into the following categories:

- Ten percent of the allotted time will be designated for innovation. All team members under contract will be granted this time without penalty to work on any activity that the person thinks will improve the success of the current or future projects. This time not only provides an opportunity to come up with great new ideas, but also serve as an incentive for team members to take risks and try out all of their ideas in the hopes that their innovations can lead to higher star power for them and thus increased demand for their services on future projects as well as higher salaries. The industry would have to address intellectual property issues that could arise from these innovation sessions. It is most likely that the individual ICEnterprises would own specific patents but would pay standard royalties to all who were documented as essential participants in the development of the new technologies.

- Ten percent of the allotted time will be designated for training. All team members under contract will be given the opportunity to take enterprise-sponsored courses for free during this time. These courses could cover technical or computing topics, new business models or processes, languages, writing, communication, teamwork, leadership or even hands-on skills such as rapid-prototyping. Some courses will be taught by volunteers or paid contractors, by faculty of local universities or by visiting experts. Each course will have an approved curriculum overseen by an industry-wide consortium, and successful completion will lead to certification that will be recognized by any of the ICEnterprises in the industry. This self-improvement time will help ensure a vibrant and constantly improving talent pool. Some of this time could also be allotted for mentorship programs in which established and rising stars could help train and motivate the next generation.

- Five percent of the allotted time will be designated for networking and collaboration. All team members under contract will be given the opportunity to learn about and help volunteer their services to any other project within the same ICEnterprise. This exchange of talent and mixing of teams will not only promote knowledge-sharing and re-use, but the cross-pollination of ideas, energy and project concepts will not only serve as a balance to the naturally competitive structure of the ICEnterprise system, but again will allow team leaders to get to know the available talent pool for hire on current of future projects.

All ICEnterprise work on a particular project is full time. Dedicated team members will only be allowed to work on one project at a time. This ensures that projects move swiftly and successfully – all knowledge-worker bottlenecks will be eliminated. In addition, the entire enterprise will work on same schedule and according to the enterprise capability development times noted above (including the CEO all team leaders, etc). The ICEnterprise will therefore work on a two-week schedule:

Week 1 – full time on primary project.

Week 2 – The first 2.5 days will again be spent on the primary project, then Wednesday afternoon and Thursday morning on innovation, Thursday afternoon on networking, and all day Friday on training.

Again, the reason for the shared schedule is to ensure that all projects execute on the same takt time – no more prioritization battles will have to be fought, and no more sub-standard team meetings will be held because key individuals are unavailable or did not have adequate time to complete the tasks they had agreed to perform. Moving in unison will create reliability, unity and shared energy throughout each project team.

Additionally, since people bid on, interview for and are contracted separately for each of the jobs they work on, all team members will be more motivated, dedicated and focused. Team members will also be able to build variety and adventure into their careers, especially if they challenge themselves by working for a number of different ICEnterprises and team leaders in a range of different capacities.

In terms of industry growth and competition, the ICEnterprise structure dramatically reduces the barriers to entry for new entrepreneurs because the capital, credibility and infrastructure requirements for new ventures will be drastically reduced. In stark contrast to the current automotive and aerospace industries where a few large, stagnant players easily maintain their oligopolistic reigns, it should be relatively easy to start an ICEnterprise because entrepreneurs will not have to invest as much capital as the established competitors. Since the new ICEnterprises will be free from the burdensome overhead structures and fixed assets, they will be able to compensate for their initial lack or reputation by charging significantly lower prices than entrenched giants. The new ventures will quickly be able to gain credibility however when customers realize that they are buying products and services produced by very talented and experienced people (hired away from the traditional suppliers) who have just been allowed to work and innovate in new ways.

In this model, stars will inevitably receive very high pay in proportion to their proven contributions to past projects, their initiative and their certified skills. Compensation contracts could be based on a fixed fee for services provided, on a bi-weekly salary rate, or on an adjustable basis with bonuses depending on product profitability, quality or other project metrics. Beyond compensation, however, it will be essential for all team members to receive very timely feedback on their performance throughout the lifecycle of any project. Team leaders will also be compelled to provide written evaluations on each team member at the conclusion of their contracts. These documents can be used by future managers to quickly sort through potential candidates, and by the candidates themselves as a means of self-improvement.

Ultimately, the ICEnterprise system would function at its highest efficiency if each team member was paid only when a customer received hardware or knowledge products in satisfactory condition. This system would eliminate hourly pay or salaries as an incentive to stimulate teamwork – team members may have different formal roles, but often may need to pitch in and do whatever is necessary to help the team satisfy its customers. Piece-rate pay schedules also stimulate teams to find innovative new ways to complete projects on time and at the highest level of quality (there would be penalties for returned products, and no pay for re-work). It would also help the ICEnterprise accurately estimate costs on a project-by-project basis – the price of each unit could easily be broken down into a list of matching expenses and profits.

This "knowledge piece-rate" could vary by star status, skills, demand, contribution and project type. For example, on a project that was shipping 40 hydraulic actuators per week, a typical engineer could be paid $27 per actuator shipped, an assembler $21, and a team leader $45.

Since the ICEnterprise system does not guarantee consistent long-term employment, certain industry-wide measures must be put into place to protect the health and welfare of its workers. Therefore, a Board of Trustees should oversee a Health and Retirement System for all employees. All team members who are on contract for more than 25% of the total time during the previous 12-month period would be guaranteed healthcare for themselves and all legal dependents for the next 12 months. In addition, they would be granted free access to any enterprise-sponsored courses and career counseling for the next five years in order to update their skills and increase their contact with current team members and project leaders so they can seek out new project contracts. After 5 years of at least 25% total contract time per year, workers will begin to vest in the industry retirement system.

In some instances, ICEnterprises could sponsor "company towns" – housing complexes that would provide subsidized living for qualified team members and their families.

All of these human benefits are in the best interest of the community of ICEnterprises that comprise any industry. In order to sustain themselves, and to offer rapid response times and high-quality products to their customers, these businesses must always be able to pull from a "critical mass" of available talent to complete any given project.

Section 5-D: Projected Strengths and Weaknesses

The ICEnterprise concept presented above will no doubt inspire conflicting reactions among different audiences. To begin, many will correctly state that the Hollywood system is not perfect. Studios often produce hugely expensive failures. Star directors are subject to extravagance and often go far over their projected budgets. Others point out that the industry has fallen into a creative rut – producing similar movies over and over again without taking risks. In general, though, the romance of Hollywood remains – it is a place where hard work, creativity, perseverance and quality are rewarded. It is a consistently profitable industry that produces huge volumes of product and continues to innovate at an accelerating pace. Each season's Oscar show draws millions of fans and inspires countless others to quit their jobs and drive across the country in search of a new life.

To a younger generation of engineers who have been frustrated and held back by the bureaucratic, seniority-based systems under which most large companies operate, an ICEnterprise system would seem to finally free their innovative spirits. To a generation of senior managers who believe that the current systems they helped create are, in fact, functioning meritocracies that reward hard work and provide value to customers, the proposition of an ICEnterprise will clash with their existing paradigms and some may reject it. There will be yet another group of people who feel that the proposed system may exploit workers. They may feel that the system unfairly forces the workers rather than the corporations to shoulder the volatility of markets and business cycles in the form of temporary unemployment. Also, they will no doubt argue that the ICEnterprise system would be rife with favoritism and politics that would make it highly exclusive and impenetrable to outsiders.

The reality is that the ICEnterprise systems lowers barriers to entry and for the first time would introduce a true labor market into the realm of engineering and manufacturing. Innovation, healthy competition, lower prices and higher quality are all the hallmarks of a free-market system, and would be in the best interest of each ICEnterprise within a given industry. Project leaders would constantly be on the lookout – scouting for new talent, new technology and new techniques in order to gain competitive advantages. Unencumbered by bureaucratic processes, the leaders would then have the authority and ability to rapidly employ these resources in the most efficient methods available.

The first drawback of a "star" system is that, by definition, not everyone can be a star. More importantly, not everyone wants to be a star. The majority of people in the workforce simply want to be paid fairly for honest work. They want to have a high quality of life for themselves and their families. This includes a high degree of job satisfaction – being able to come home each night feeling energized and accomplished rather than drained and resentful – and a feeling of financial stability.

While some traditional companies have gone to great lengths to provide rewarding careers and surroundings to their employees, many take their work force for granted – hiring and firing tens of thousands of workers on each end of the economic cycle. But, providing job security can have drawbacks as well. Many workers become complacent when treated poorly or put in positions where they have little authority or accountability –soon their lifestyle needs quickly outpace their desires to put forth their best efforts each and every day. Over time, even the most creative and conscientious people will focus their energy on their personal life instead of the company's interests if their ideas are neglected or poor processes or leadership stalls their efforts. Placed in the right enterprises, these workers could unlock their latent productivity and still maintain or even increase the quality of their personal and professional lives.

Creating an ICEnterprise and an industry of ICEnterprises will require tremendous leadership, courage and hard work. It will take time, and the teams will have to learn and adapt, but it is inevitable that a functioning ICEnterprise would dominate its traditional competition in any business performance metric. If one small group such as the RTCE team can overcome adversity to change the way people work, think, are measured and perform within a major US corporation, one ICEnterprise could do the same within an industry or the economy as a whole.

Chapter 6: The Integrated Concurrent Enterprise – Implementation

As with MATE-CON, the leap from theoretical process to a continuously profitable and competitive enterprise requires leadership, knowledge, vision and hard work. This chapter will therefore present an implementation guide for those wishing to create an ICEnterprise from the ground up or for those wishing to help transform an existing decomposition-based organization into a fully Integrated Concurrent Enterprise.

Section 6-A: The ICEnterprise Charter

The first objective of an ICEnterprise is to create a set of tools, processes and skills that facilitate Best Value Solutions. These are based on the integration of:

New Customer Preferences and Changing Business Objectives

Design Engineering Experience and Untethered Creativity

Enhanced Value Chain Capabilities and Applied Knowledge

In this new paradigm, the key partners or stakeholders must be identified, and the needs and assets of each must also be known to all involved. In general, these partners can be grouped into three categories:

"Customers:" Organizations that are end users or that link the ICEnterprise's products to the end users

Examples: Traditional Corporate Customers (system integrators or end-product manufacturers), Governments, Industrial, Commercial or Personal Consumers

"Systems Engineering:" Teams or organizations that create designs which link the needs of the customer with the capabilities of the enterprise

Examples: Design Engineering, Product Line Specialists, Marketing and Industry Partners

"Value Chain:" Teams or organizations that transform designs into shipped products or processes.

Examples: Operations Department, Supply Chain Management, Quality Department, Internal and External Suppliers and Industry Partners

The current methods are trapped by some unique barriers that are exacerbating the current business challenges:

- **RFP's** (Request for Proposals) do not adequately represent the preferences or business objectives of the Customer
- **Proposals** do not adequately convey the full set of solutions from the systems engineers to the potential customers, nor do they explain the dynamics of complex trade decisions
- Once a design is ready for **cost and schedule estimates** from the value chain, it is too late to create radical savings

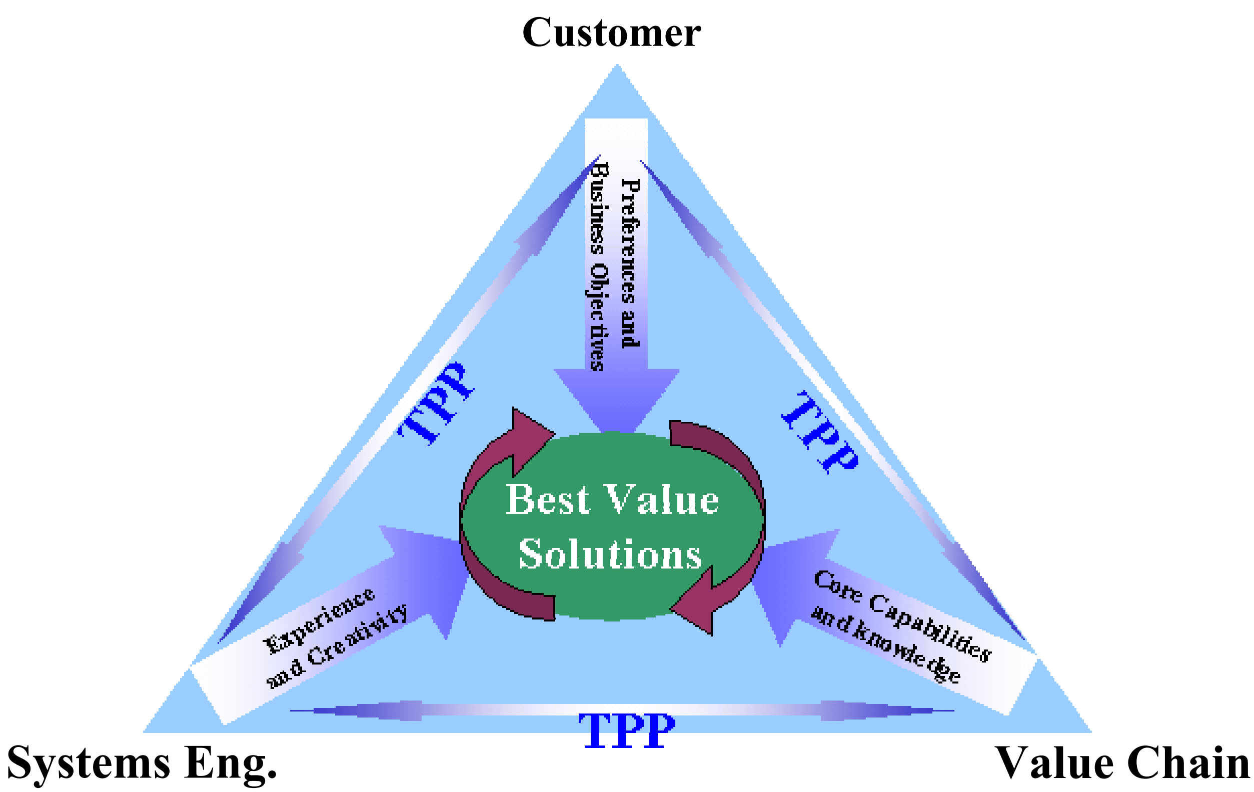


Figure 6-A-1: ICEnterprise Integration Model

Based on the need to unite and align these diverse interests, an ICEnterprise cannot lie within the rigid organizational boundaries that define traditional corporations. This vision will require a number of powerful and visionary leaders to come together, defy current paradigms and corporate metrics, and work passionately to build a new system.

There will be three Enabling Elements for an ICEnterprise. These capabilities must be developed and employed as a system (an Enterprise-Perspective and an Integrated Approach) in order to provide best value solutions to all stakeholders. These three elements are derived from the technology, people and process model presented earlier:

People: A high-performing Integrated Concurrent Engineering work environment. One that frees people to do what they do best, encourages and rewards innovation, allows learning and feedback, and consists of high-caliber or "star" system designers.

Process: The use of MATE-CON or a similar system that enables clear visualizations of complex inter-relationships in order to facilitate communication between System Designers, Customers and Leadership.

Technology: The creation of an overarching information system that shares, parametrically-linked but configuration-controlled information on every aspect of the enterprises designs, processes and assets. This Universal Knowledge System (UKS) must be simple, intuitive, easy to maintain, and constantly visible.

Section 6-B: Transformation to an ICEnterprise

Guiding the evolution of a traditional organization into an ICEnterprise will require vision, leadership, communication and tenacity. Not only must the leaders of such an endeavor be willing to break all the rules that they were taught throughout their careers, but they must also place absolute faith in the people they lead.

In general, there will be 6 phases of transformation:

The Six Phases of ICEnterprise Transformation		
Phase 1	Approx. 6 months to 1 year	Product Development IPT: The leaders should pull together a star team from **all** aspects of the company's operations to design and produce the next generation product for the company. As an entity, the team should report directly to the CEO of the company. All team members will be assigned on a full-time basis, will be co-located and will be evaluated based on the technical and financial performance of the new product.
Phase 2	Approx 1 year	Integrated Concurrent Engineering Team: The Product Development IPT shall then implement ICE techniques as described in steps 1.0 through 4.2 below.
Phase 3	Approx. 1 year	Implementation of MATE-CON: As described in steps 5.0 through 5.1.16 below, the MATE-CON process or a similar derivative can be implemented in any high-performing ICE team throughout the company. This new capability will be adapted to each particular team's needs, but can add tremendous power to the design process by increasing the powers of analysis, communication and decision-making for all team members.
Phase 4	Approx 1 to 2 years	Expansion into Other Functional or Business Processes: After the Product Development IPT has become a high-performing ICE team; team members can begin to share their new processes with others in the organization. ICE labs can be established to accomplish other tasks such as integrating suppliers, designing subsystems, or creating new logistics networks. Some of the original team members can be coaches for these new teams after they train others to take their places on the original team. Refer to step 6.0 below.
Phase 5	Approx 2 to 4 years	Transition to Project-Based Organization: Using the ICEnterprise Vision from Chapter 5, Section C as a guide, the company should begin to transform from a functional or matrix organization into a purely project-based entity. This should begin when the leaders select star teams to execute new projects autonomously – giving them the freedom and authority to complete the tasks in the best ways they see fit. The first teams would lease offices off-site from the company and hire away key team members as necessary. They could choose to use the company's existing manufacturing capabilities by sectioning off parts of the existing factory for their sole use or by moving assets into their new location.

The Six Phases of ICEnterprise Transformation		
Phase 6	Approx 2 to 10 years	Shedding of Traditional Corporate Boundaries: After the company has successfully completed a number of projects under the new operating concept, it can begin to slowly release assets and employees who have not been hired into any of the past projects and finally operate as a mature ICEnterprise

The most effective project implementations begin with People. Once a leader is confident that a skilled and motivated team is in place and has been given clear objectives and authorities, he or she can then let the team choose and adapt the most appropriate processes and technologies to complete the assignment. No two conceptual design projects are alike. As stated by (Neff and Presley, 2000), the creators of the Concept Design Center at the Aerospace Corporation:

> "Computers cannot replace people in conceptual design. Rather, a good information system supports human strengths and compensates for human weakness"

In an Integrated Concurrent Engineering environment, "people are freed up to do what they do best: create innovate, exercise judgment, and communicate. The result is better designs with less time and money."

NOTE: Each task in the detailed process flow presented in this Section has been classified into one of the TPP categories. As the implementation moves forward, the leadership should avoid becoming fixated on any one aspect of the project, and instead remember to spend equal time on tasks in each of the three areas. A specific role is assigned to each task. This is the person or group that should lead (and participate in) the activities described.

Upon the decision to initiate a new CIEL environment, Executive Management of the business unit should initiate a process similar to the following, however it should be tailored to meet the specific needs or circumstances of the enterprise that is undergoing transformation:

1.0 Initiation of New ICE Project

Role(s): Executive Management

Input: Decision (or approval) to initiate new Integrated Concurrent Engineering Team

Initialize the Project and assign the necessary team members.

1.1 Review Applicability (PROCESS)

Role: Executive Management

Review Product Development Process and Product Portfolio to locate a product family that could be designed in an Integrated Concurrent Engineering environment. There should be one or more highly complex, yet relatively standard products or systems that are redesigned for each new application.

1.2 Communication to Rest of Organization (PEOPLE)

Roles: Executive Management, Project Leader

Call the organization together to explain the ICE concept, the top-level objectives of the ICE project, and the priorities the project will have over other business processes.

Convey the business needs that are driving the change and explain the vision for a new way of doing business.

Make both nominations and solicit volunteers to lead and participate in the project.

1.3 Assign Leadership (PEOPLE)

Role: Executive Management

Assign an experienced, energetic and well-respected Project Leader from among the volunteers and nominees.

1.4 Determine Project Objectives (PROCESS)

Roles: Executive Management, Project Leader

Based on the type of product family, recent organizational objectives and customer feedback, determine the objectives of the ICE project.

Write a team charter document that clearly explains these objectives, the responsibilities and accountabilities of the team, and the priority the project will have over other existing business processes.

1.5 Assign Key Subsystem Team Members (PEOPLE)

Roles: Executive Management, Project Leader

Based on the complexity of the product to be designed, identify the key subsystems that will be included in each new system design project.

Assign an experienced designer from among the volunteers to represent each subsystem. This "lead subsystem designer" will be assigned full responsibility for all design decisions relating their subsystem.

For the initial phase of the project, each team member will be assigned to the ICE development on a full time basis – ensure that each team member selected will be available. Team members should not only be highly proficient in their technical area of expertise, but should also be comfortable with computers, able to work in a fast-paced, high energy team environment, and be very open minded.

The team leader may also want to draft a head developer to lead the technical portion of the team's operations as well as a process facilitator, or "design lead," to serve as a process guide during each ICE session.

In addition, assign a responsible individual for each of the following analysis areas: top-level system engineering, cost, schedule, operations (manufacturing), and supply chain.

Finally, assign a customer representative and a system administrator.

As noted by the designers of the Concept Design Center, or CDC, at the Aerospace Corporation (Neff and Presley, 2000), team members should be chosen carefully and placed into the right environment:

Types of team members:

> "From our CDC experience, we have learned that a conceptual design team lead can run into serious problems if [the team leadership] assumes that a detailed design specialist can also do up-front conceptual design"
>
> "Our experience … the gap between the way of thinking used by specialists doing conceptual design versus specialists doing detailed design can be significant."

Therefore, an ICE team will need internally motivated people. Team members "will encounter the following 'space' during conceptual design: ambiguity, uncertainty, instability, an overwhelming number of options, and a shortage of needed information including system level requirements… Member activities include identifying and trading options, challenging the original set of assumptions, making assumptions about data in the absence of them, working to build an understanding of how your part fits into the system a s whole, and continuously communicating with the customer and members of the design team"

Other characteristics: "a temperament for conceptual design, the right technical skills, a desire to be involved and to contribute, a "can-do" attitude, a willingness to make time to be involved, ability to work well on teams, and a collaborative nature."

Maintenance: Regular surveys should be used to check on the team dynamics.

New team members bring fresh ideas, but must have a forum to openly talk about them – so they don't hold up design sessions. Environmental factors that help foster creativity:

- "Trust and respect for each other
- Individuals believing they can speak up without fear of punishment or reprisal
- An atmosphere of experimentation and craftsmanship
- Failure is not treated as a crime
- Supportive management
- Low levels of cynicism and harsh judgments"

The team leader should work with each new team member to craft a set of initial roles and responsibilities that will help set expectations for each team member and serve as a basis for personal and team-wide performance evaluations.

1.6 Determine Project Budget and Schedule (PROCESS)

Roles: Executive Management, Project Leader

Based on the number of subsystem representatives, the complexity of the product to be designed, determine the project budget and schedule for creation of the Integrated Concurrent Engineering team.

1.7 Communication to Team (PEOPLE)

Roles: Executive Management, Project Leader

Pull the initial ICE team together for a project kick-off meeting.

Explain the objectives for the Lab and the business needs that are driving the change.

Discuss the new responsibilities that each team member will have, and the absolute necessity for the team to take risks in order to radically re-shape the way that the company does design work.

2.0 Project Kick-Off Workshops (PROCESS)

Role(s): Project Leader, Initial Team Members

Input: Team Charter

Output: Initial Lab concept and plans

2.1 Benchmarking Field Trip (PEOPLE)

Roles: Executive Management, Project Leader, and Initial Team Members

Visit a working Integrated Concurrent Engineering Lab.

Spend a day observing a working team in action, asking questions, determining the strengths and weaknesses of the Lab, and what lessons the existing team learned during their early phases.

2.2 Field Trip Debriefing – Draft Laboratory Design (PROCESS)

Roles: Project Leader, Initial Team Members

Before beginning the detailed design of their new lab, the team should spend two or three days sitting down together to frame the overall high-level design of their new lab. The outputs of these discussions are not fixed decisions, so the team leader should monitor the level of detail to which each topic should be covered. Subsequent workshops will be convened to finalize the details of each topic. The team should somehow document their ideas and decisions so that there is a clear understanding among all team members and for future reference. The issues addressed should include the following:

<u>Team Norms</u> – what hours, work environment and behaviors will be created and abided by. The team also needs to agree how decisions will be made and how conflicts will be addressed.

<u>Team Scope</u> – From the initial project objectives, the team should determine what standard products or systems they would design and to what general level of detail.

<u>Team Objectives and Metrics</u> – The team should have input into the goals and performance measures they hope to achieve within a given time frame.

<u>Team Facility</u> – Because construction could take several weeks, the team should use this early opportunity to sketch out their vision for their concurrent engineering facility. They should decide approximately how the room(s) will be laid out and what equipment they will need.

<u>Team Design Philosophies</u> – All engineers approach problem-solving slightly differently. The team should therefore discuss general guidelines for designing a complex system and for the supporting calculations. A margin philosophy should be discussed. General practices concerning estimates, source materials and traceability of calculations should be figured out. An overall design strategy should be established.

Sources such as (Shenhar and Bonen, 1997) could help guide the team to a new approach to design – building a philosophy of flexibility and built in iterations depending on the type and scope of each new project rather than a one-size fits all rigid approach

Browning and Eppinger (2002) and others suggest new "value-based design" approaches – which incorporate strategic and cost models into the technical design iteration loop.

Design Session Process – The team should next lay out a general concept for their new design process: who will be involved in what steps, what decisions will be made when, what tasks will and will not be included in the scope of different projects, etc.

Information Exchange – The team needs to establish some general requirements for an information exchange architecture so that they can shop for or write their own design software.

2.3 Laboratory Information Architecture Design Workshop (TECHNOLOGY)

Roles: Project Leader, Initial Team Members

Determine and document the information architecture the team wishes to use to pass detailed design information among them during the design process.

Team members should consider the following issues:

- How they will input requirements and preferences from customers, to flow these down to each sub-system, then to verify in real time how a proposed design performs against these criteria.
- How to control margins from a top level
- How to verify that they are each working with real-time data from other subsystems
- How to link parametric models to each other and to analytic tools.
- How to link design data to 3-Dimensional tools so that designs can be visualized in real time.

- How to create parametric models and deal with out-of-limit errors
- How to create a stable design environment so that if one subsystem is outputting large errors, others will be able to detect them and be able to continue their work with minimal interruption.
- How to access cost, inventory and delivery data from the supply chain
- How to estimate system cost and schedule
- How to incorporate design-for-cost and design-for-manufacturability philosophies
- How to record the output of each design session in a simple yet accurate manner
- How to trade competing designs against each other in an objective manner
- How to balance re-use of design work against innovation
- How to verify the output of the design lab against previous designs the company has created.
- How to incorporate statistically accurate risk assessments into the system analysis

2.4 Laboratory Physical Architecture Design Workshop (TECHNOLOGY)

Roles: Project Leader, Initial Team Members

Locate an appropriate facility for the design lab. The main room should be large enough to comfortably accommodate the entire team at one time, but should not be too big that it is difficult to hear one person speaking (without a microphone) or to clearly see a whiteboard or projection screen from any location within the room.

The lab should be surrounded by adequate office space to seat the entire team, support staff and other important organizational members.

The team should create a layout including spaces for workstations, projectors, screens, a printer, whiteboards, phones, a conference table, and a refreshment station.

The team should also consider future expansion and plan accordingly.

While waiting for construction, the team should obtain a development facility such as a large conference room. The team can then operate from a bank of networked laptop computers and projectors.

2.5 Software Selection Workshop (TECHNOLOGY)

Roles: Project Leader, Initial Team Members

Explore the commercially available concurrent engineering software platforms. (NOTE: This can be performed individually or in sub-teams. Team members should visit sites that use potential software packages and should obtain trial versions for testing. Each sub-team can then report to the entire group during the actual workshop.)

Current Design Integration Software Vendors and Packages	
Software Names	**Vendor**
ICEMaker©	SpreadsheetWorld (http://www.spreadsheetworld.com)
CO®	Oculus Technologies (http://www.oculustech.com/)
RenderBeast	Evans & Sutherland (http://www.es.com)
MATRIXx	National Instruments (http://www.ni.com)
Cradle-4	3SL (http://threesl.com)
Real-Time Studio®	ARTiSAN Software (http://www.artisansw.com)
CORE Systems Engineering Tool	Vitech Corporation (http://vitechcorp.com)

Current Design Integration Software Vendors and Packages	
Software Names	**Vendor**
The SEER™	Galorath Incorporated (http://www.galorath.com)
ModelCenter®	Phoenix Integration, Inc. (http://phoenix-int.com)
GoldSim Pro	GoldSim Technology Group (http://www.goldsim.com/software)

The team should then discuss the strengths of each potential software with regard to the chosen information architecture and the team objectives and budget. Finally, choose a platform or custom design and initiate the requisition.

2.6 Roles and Responsibilities Workshop (PEOPLE)

Roles: Project Leader, Initial Team Members

The team should take time to establish a written set of "R&Rs" (Roles and Responsibilities) for each team member – including the leadership. This activity will strengthen the confidence that each team member will have in the process. By knowing that all of the key design tasks will be completed, and by knowing who is responsible for specific deliverables, the team can move forward with each new design quickly, efficiently, and with very high quality.

Note that it is absolutely critical to evaluate the scope of work that each subsystem will be responsible for during the session. Since each design session encompasses a number of parallel tasks, the approximate time required for each task must be taken into account when the subsystems are partitioned. The entire team cannot be forced to wait for two hours while one person performs an analysis step. In order to prevent these situations, the level of detail that is required must be examined very critically. In some cases, detailed analyses can be split into sections so that preliminary information can flow to others. In other scenarios, two or three clients may need to be created to handle the work of one subsystem. Last, more efficient models or techniques will need to be invented to enable the system to work concurrently.

2.7 Input / Output Workshop (PROCESS)

Roles: Project Leader, Initial Team Members

Team members should each gather a list of all the data points and design variables that they require in order to complete their respective design tasks.

The team should then meet to create a global "Needs-Squared" or N^2 diagram (see figure below) that matches the data needs of each subsystem with an agreement to provide that information from another subsystem. In the figure, the list of all subsystems or other participants is placed in both the vertical and horizontal axes. The intersecting blocks then represent the number of design variables or pieces of information that will be provided by the "publisher" as outputs to the "receiver" as inputs. The figure represents a summary so that the team can visualize the flows of information and the important coupling between different team members, but it is up to the team to actually assign and label each individual piece of information that will be exchanged.

This process must continue until all subsystem data needs are identified and met, however it should be noted that, inevitably, new data requirements will emerge during nearly every design session. Thus the system should be able to handle these requests in real time.

Depending on the status of the information exchange software that the team has chosen, this workshop can be both a working and learning session. If the software is available, the team can begin to learn it through experience. If the team plans to use other, existing engineering or analytical models, they can also be brought to the session so that the inputs and outputs can be properly integrated into the N^2 system.

• Receiver

• Publisher

	Subsystem 1	Subsystem 2	Subsystem 3	Subsystem 4	Subsystem 5	Subsystem 6	Subsystem 7	Subsystem 8	Subsystem 9	Subsystem 10	Subsystem 11	Subsystem 12	Subsystem 13	Subsystem 14	Subsystem 15	Subsystem 16	Subsystem 17	Subsystem 18	Subsystem 19	Subsystem 20
Subsystem 1		41	72	18	1		36	1		44	5	2						36	4	
Subsystem 2					2		4		1					20			11	4		
Subsystem 3	74			458	16		42		17	2	50			420	80			42	5	26
Subsystem 4	79		192		5		54		2	7	102			192			8	54		
Subsystem 5						28	2											2		
Subsystem 6	4	4	2	5	4		15	8	1		7	5				6	6	15		3
Subsystem 7																				
Subsystem 8	3				3												4		2	
Subsystem 9				192			1				2			608			4	1		2
Subsystem 10	3				16		18				13	1						18		
Subsystem 11	2	1			8		2			8							6	2	41	
Subsystem 12					2	8	16	2		12	4						3	16	2	
Subsystem 13					4		2		1					42			3	2		
Subsystem 14	12	60	389		1	4	121		95		74		208			3	30	121	5	244
Subsystem 15	16	35	209		16		5	152	25	1810	3		12	5				5	149	11
Subsystem 16					1		20			11	8			2			1	20		
Subsystem 17		42		6		52	52	35	6		52		52					52		
Subsystem 18	1	5	1	1	3	11	45	12	3	5	9	9	2			18	7		10	7
Subsystem 19					3												44			
Subsystem 20	6		2	3			5		4	2	8			34		4		5	3	

Figure 6-B-1: Sample Needs-Squared analysis diagram. Numbers represent the total data items needed by each "receiver" that are provided by each "publisher."

3.0 Subsystem Client Development (TECHNOLOGY)

Role(s): Project Leader, Initial Team Members

Input: Needs-Squared Analysis, All Workshops in Step 2

Output: Validated Subsystem Client Models

NOTE: Some of the task descriptions below refer specifically to the ICEMaker information exchange software employed by the ICE team. As stated previously, other teams may find other tools that are more appropriate for their *particular needs. These task steps are therefore offered as a general guide and not firm requirements.*

In the case of RTCE, ICEMaker was chosen because of its elegant simplicity, its low cost, and the availability of experts who could help facilitate the team through the implementation process and rapidly troubleshoot any potential problems.

3.1 Template Creation (PROCESS)

Roles: Project Leader, Initial Team Members

Based on the architecture analysis and the software chosen in previous steps, create a set of standard templates that each team member can use to construct their subsystem models, or "clients." Refer to the Figure below for a generalized version of an ICEMaker Client.

The purpose of the template is to ensure that all clients are constructed based on a standard set of assumptions and techniques. As the system evolves, new, or updated models can be easily exchanged for older models (labeled "Level 1" etc in the figure). Note that the team should also specify as a group the level of fidelity that each detailed design level would represent. This is extremely important – the accuracy of the entire design system can only be as great as that of the least accurate client model. There may be no reason to spend excessive amounts of time and money developing a few particularly detailed models if the fidelity of the inputs are much more general.

This modular structure also enables error checking and isolation for debugging. During the design sessions, the standard appearance of each client will enable team members to quickly interpret information from other subsystems, and to solve problems together. Finally, the common architecture will enable new team members to be trained efficiently.

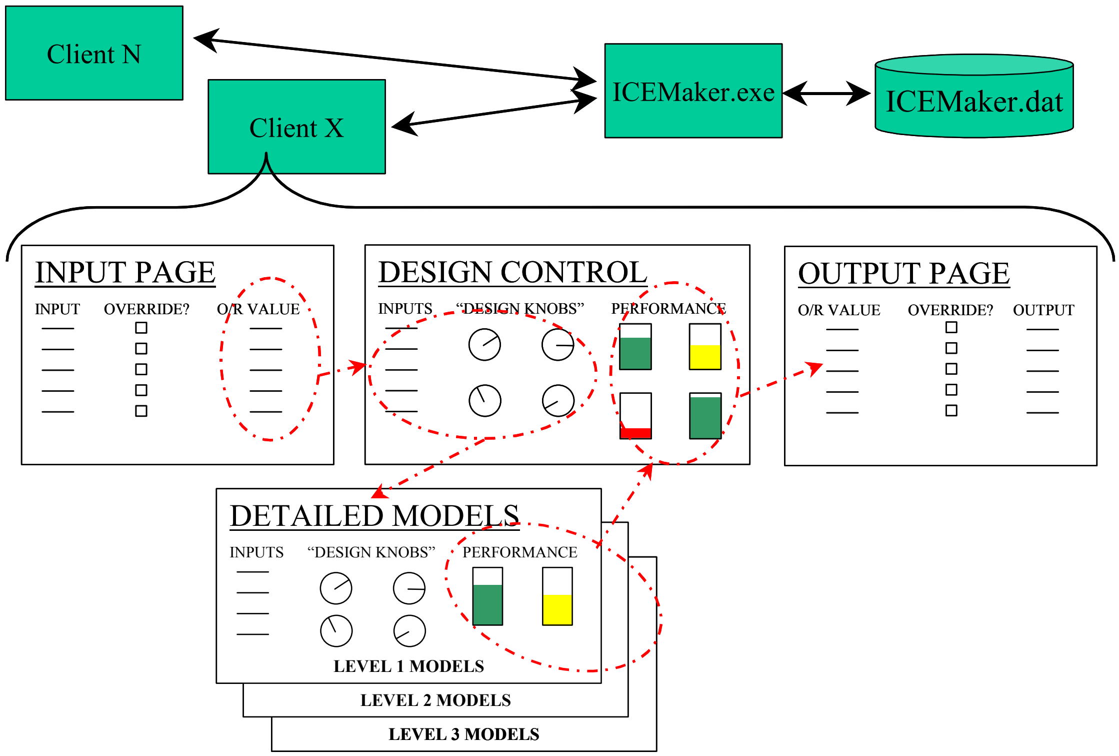


Figure 6-B-2: Sample Client Architecture in an Integrated Concurrent Engineering process using ICEMaker© data-exchange software.

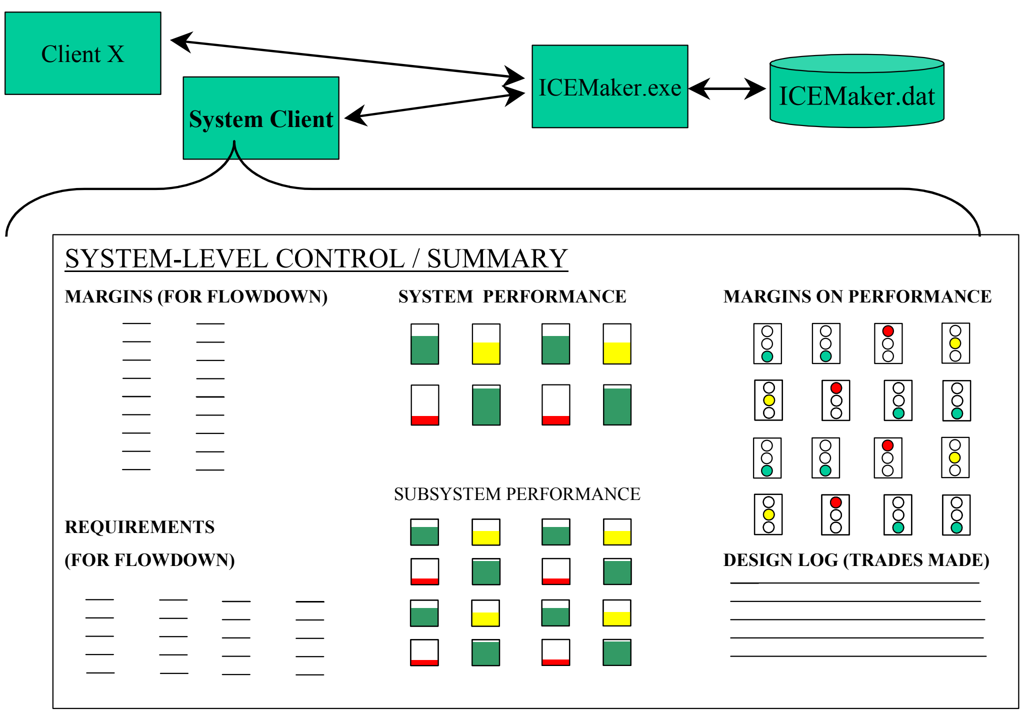


Figure 6-B-3: Sample Top-Level System Client Architecture in an Integrated Concurrent Engineering process using ICEMaker© data-exchange software. This master control panel would often be projected onto a screen so that the entire design team can monitor the performance of their proposed design.

3.2 Subsystem Client Development (TECHNOLOGY)

Role: Project Leader, Initial Team Members

Each subsystem representative should develop his or her client based on the group template.

The System-Level Client should include the ability to flow down system requirements and margins to subsystem clients, and then to collect and analyze top-level system performance metrics and margins. In addition, many ICE teams have implemented very simple 3-D rendering tools so that the design team can quickly visualize the product they are designing. Finally, the System client should contain the functionality to coordinate and analyze system-level design trades. Refer to Figures below for conceptual system client designs.

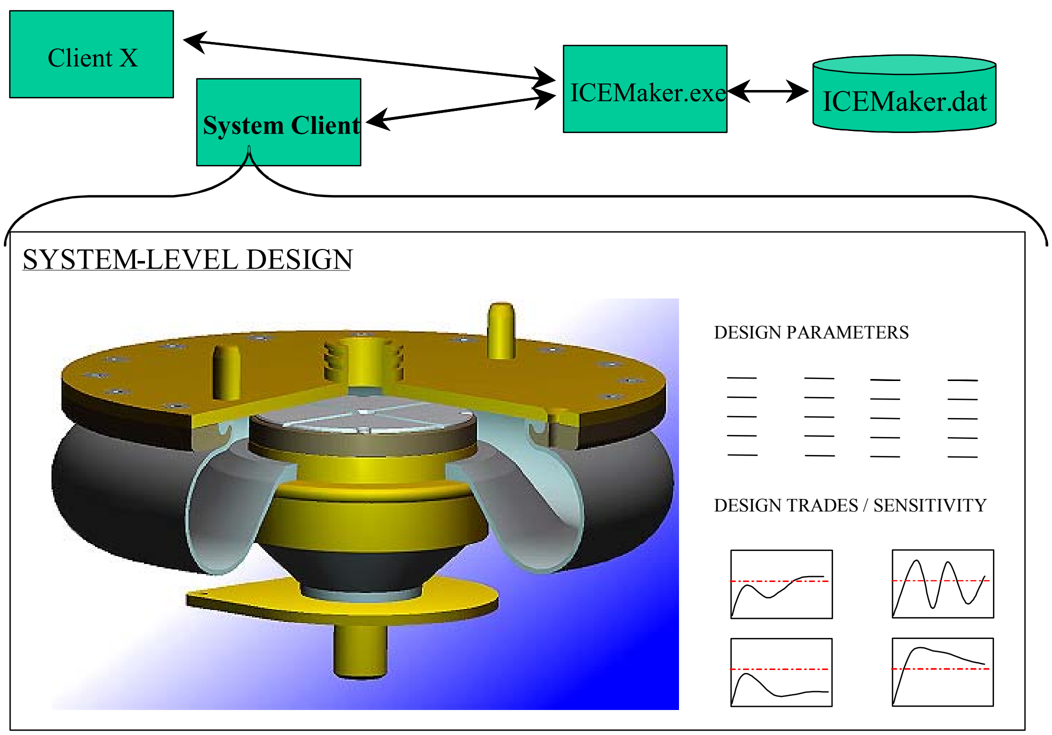


Figure 6-B-4: Sample System Client 3D Architecture in an Integrated Concurrent Engineering process using ICEMaker© data-exchange software. The picture represents real-time 3D rendering of the design so that the team can visualize their product as they work through the design process. This worksheet could also be projected continuously in order to provide each team member greater visibility into the proposed design.

3.3 Subsystem Client Validation (PROCESS)

Role: Project Leader, Initial Team Members

In order to obtain buy-in from the rest of the organization, and to further communicate the vision for and progress of the Integrated Concurrent Engineering project, a series of subsystem client "design reviews" should be held in each functional group of the organization.

Each of these reviews should consist of a presentation of the overall system architecture that the team chose, the design philosophies the team will operate under, and a review of the goals of the project. Then, the particular subsystem client should be presented in detail.

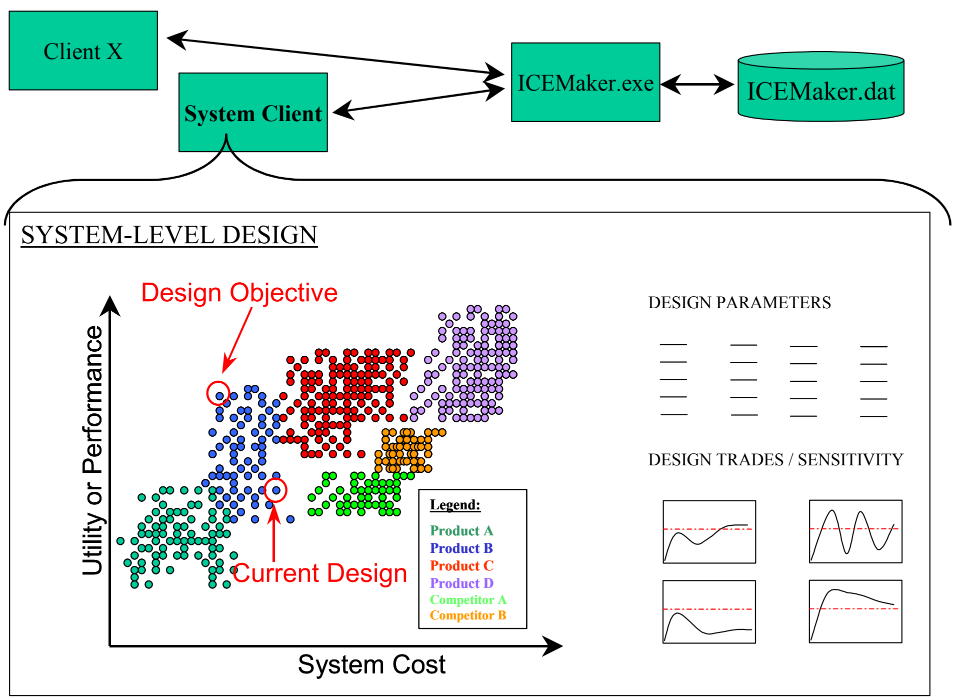


Figure 6-B-5: Sample System Client MATE-CON Architecture in an Integrated Concurrent Engineering process using ICEMaker© data-exchange software. This worksheet could be projected periodically in order to allow the team to visualize how their proposed design compares to other potential design options (and competitor offerings) as measured by the customer's preferences or utilities.

The models, assumptions and performance parameters should all be reviewed, and the team member should solicit technical and conceptual feedback from the rest of the functional group. If some standard models already exist within the group, they can be identified and incorporated through this process. Alternately, models developed for the client could be distributed to the group as new standard tools for use on other projects.

3.4 System Integration and Validation Workshops (TECHNOLOGY)

Role: Project Leader, Design Lead, and Initial Team Members

In order to pace the development of the subsystem clients, and to test their validity, a series of (weekly) workshops should be planned. Each workshop should serve as a test of both the technical workings of the new system as well as the group process that accompanies it. The process followed here will serve as a warm-up for actual design campaigns that the team will face in the future. At this point, a new role can be introduced if necessary – the team facilitator, or “Design Lead.” This person should have the sole responsibility of leading the design session so that the process is followed. This role will be in contrast to the technical, or “system lead” who operates the system client and is the final authority on all technical matters.

The basic objective of each workshop will be to “design” an existing, successful product using the new process. The output of the session can then be compared to the actual design, and the differences between the two can be used to “calibrate” the new system. Each workshop will also be a test of the flow of a real concurrent engineering design session – as mentioned previously, tasks must be performed in parallel, and creative solutions may need to be implemented if the team finds that it is consistently waiting for one task or subsystem to complete a crucial segment of the work.

The general process flow for a System Integration and Validation Workshop should be as follows:

Workshop Day – minus 5: Distribute the top-level requirements for the validation product. These materials should resemble the level of detail that a design team would typically receive at the beginning of the existing design cycle (for example: customer specifications, market research, target costs, other internal targets such as lead-time or technology levels, etc).

Workshop Day – minus 4: The team or a subset of the team will meet to discuss the design challenge and set performance targets and other objectives for the design session. In addition, the desired level of detail for the session, and the number and type of trades or sensitivity analyses will be determined. This information is documented and communicated to the remainder of the team members.

Workshop Days – minus 3 to minus 1: Team members work on their subsystem clients to make sure that each one will be capable of analyzing the proposed design and trade studies. These tasks also must be completed within the time given for the session. In some cases, certain trades will need to be "pre-loaded" so that valuable design session time is not wasted initializing worksheets or inputting data.

Workshop – Hour 1: The team should gather in their design room. The project leader will then walk through the top-level requirements of the design in question, and re-iterate the design objectives and metrics. The initial design requirements are sent out to all clients, and the design process begins. Each client should verify that they are receiving the correct design information from the systems client and other clients, and that their design outputs are being contributed to the system accurately.

Workshop – Hours 2 and 3: The monitors the progress of the design by viewing the system client's top-level metrics. Problems of information flow or client deficiencies are handled as a team. In some cases, if a particular function is not working and cannot be fixed in a timely manner, the over-ride functions can be used to continue work as a group using some assumed data instead of actual calculations. These bugs can then be fixed off-line after the session. The team periodically pauses work to "go around the room" and allow each team member to summarize their progress or any issues they are encountering.

Workshop – Hour 4: The team converges to a design and performs trade studies or sensitivity analyses as planned. The results are documented and archived. The team performs a final "around the room" discussion regarding the process flow and ideas for improvement.

Workshop – Day 2: The team meets to compare the output of the design session to the actual design that had previously been done by the company. The team makes note of any inconsistencies and makes recommendations for improvements to the system, process or individual clients.

3.5 Process Definition (PROCESS)

Roles: Project Leader, Initial Team Members

Once the validation studies begin to flow smoothly, the team can meet and codify the process they will use on a recurring basis to design new products. There are many creative processes that can be employed to help smooth the flow of each design campaign – depending on the particular level of detail required, the available budget and schedule, and the type of product to be designed.

Additionally, the team should agree on team norms such as advance notification of new design sessions, attendance policies, how to make decisions (voting vs. authority of project leader, etc), and training of new members. Process Metrics should also be established so that the team can monitor their performance and be rewarded accordingly.

Finally, the team needs to establish a configuration-management scheme for the design tools they have created. This process will enable the team to avoid repeating mistakes that have been fixed, and to be able to accurately re-examine old designs even if the tools change over time.

3.6 System-Level Design Review (TECHNOLOGY / PEOPLE / PROCESS)

Roles: Executive Management, Project Leader, and Initial Team Members

After an appropriate number of validation workshops are completed and the team is confident that its tools and processes are capable of handling a new design task smoothly and efficiently, the entire system should be presented to the Executive Project Sponsors and the rest of the organization.

Team members should explain how their system works and how it addresses the key challenges that the organization faces. The team will present the details of their process and product metrics and establish lines of feedback so that the organization can use the data that are produced by the design sessions and provide input to the team regarding the quality of their output.

4.0 Long-Term Implementation (PROCESS)

Role(s): Executive Management, Project Leader, all Team Members

4.1 Team Process Maintenance (PROCESS)

Role: Project Leader, all Team Members

Periodically, the Integrated Concurrent Engineering team must meet to review their process metrics and organizational feedback. A plan for improvement of the concurrent engineering process and the technical tools (clients) can be established and followed through.

4.2 New Team Member Training (PEOPLE)

Role: Project Leader, all Team Members

When new team members are added, it will be the responsibility of the entire team to help train the new members and to help them understand the objectives and norms of the concurrent engineering lab. New members should be required to sit in on working design sessions in order to learn the process before they attempt to operate any of the technical tools.

NOTE: The following Tables give conservative estimates of the amount of time, labor and materials that would be required to form an Integrated Concurrent Engineering team as described in Phase 2 above (steps 1.0 through 4.2). For a high-performing Product Development IPT, the labor hours would be significantly less than the estimates.

Phase 2 (ICE Team) - Estimated Effort

Step	Description	Number of People	Duration (days)	Total Labor Hours
1.0	Initiation of New ICE Project			
1.1	Review Applicability	5	0.25	10
1.2	Communication to Rest of Organization	50	1	400
1.3	Assign Leadership	3	0.5	12
1.4	Determine Project Objectives	2	2	32
1.5	Assign Key Subsystem Team Members	2	5	80
1.6	Determine Project Budget and Schedule	2	5	80
1.7	Communication to Team	20	0.5	80
	Totals:		**14.25**	**694**
2.0	Project Kick-Off Workshops			
2.1	Benchmarking Field Trip	20	1	160
2.2	Field Trip Debriefing – Draft Laboratory Design	20	3	480
2.3	Laboratory Information Architecture Design Workshop	20	2	320
2.4	Laboratory Physical Architecture Design Workshop	20	1	160
2.5	Software Selection Workshop	20	4	640
2.6	Roles and Responsibilities Workshop	20	2	320
2.7	Input / Output Workshop	20	2	320
	Totals:		**15**	**2400**
3.0	Subsystem Client Development			
3.1	Template Creation	20	2	320
3.2	Subsystem Client Development	20	20	3200
3.3	Subsystem Client Validation	40	3	960
3.4	System Integration and Validation Workshops	20	15	2400
3.5	Process Definition	20	3	480
3.6	System-Level Design Review	35	2	560
	Totals:		**45**	**7920**
4.0	Long-Term Implementation			
4.1	Team Process Maintenance (per month)	20	2	**320** (per month)
4.2	New Team Member Training (per month)	5	1	**40** (per month)

Phase 2 (ICE Team) - Estimated Schedule

	Description	Approx. Schedule Duration (months)
1.0	Initiation of New CIEL Project	1
2.0	Project Kick-Off Workshops	1.5
3.0	Subsystem Client Development	4.75
4.0	Long-Term Implementation	On-going
	Total:	7.25 months

Phase 2 (ICE Team) - Estimated Material

Description	Estimated Cost Range
Facility – construction, Intranet, etc	$5,000 – 50,000
Computers, phones, Printers	$25,000 - $75,000
A/V equipment (switching / projectors)	$5,000 - $20,000
Software	$0 - $50,000
Total:	**$35,000 - $195,000**

5.0 Implementation of MATE-CON

Currently, MATE-CON has not been successfully deployed in a commercial venture. There are several reasons for this, beginning with the fact that the process has only recently been developed. It is also complex to understand and adapt, and expert practitioners are rare. Since MATE-CON is an extension of ICE techniques, it's implementation would be best suited in companies that currently practice ICE – of which there are only a handful in the world today. MATE-CON can easily be implemented incorrectly, so a trained process facilitator must work with the team so that they understand the true power and potential pitfalls of utility theory.

5.1 Recommended Implementation Steps

For a high-performing ICE team, implementation of MATE-CON could be a seamless evolution. The following is a recommended srategy based on the experiences of the author (who is currently working on such a project for a major US corporation):

5.1.1 Team Leader(s) present a compelling need for MATE-CON to the ICE team

5.1.2 Assign two well-respected team members to create a prototype tool and process

5.1.3 A senior manager who has strong relationships with customers and the team (a "heavy-weight")

5.1.4 A newer engineer who has strong computer skills (Matlab, VBA and Access) and the respect of his peers Have them work closely with a MATE-CON expert

5.1.6 Give periodic presentations to the ICE team

5.1.7 Use examples from current projects to show how MATE-CON could have added even more value

5.1.8 Listen to input from team and ask them to help implement their ideas

5.1.9 Slowly bring the process and tool on-line during ICE sessions

5.1.10 Operate in the back-ground at first

5.1.11 Test out while not disrupting normal sessions

5.1.12 Create own attributes and utility curves

5.1.13 Choose a strategic first customer (can be internal)

5.1.14 Offer benefits of process for free in exchange for trial iterations and feedback

5.1.15 Implement full-scale with excitement and energy

5.1.16 Let the team run with it and improve it as they go

Once up and running, strong team leadership, and a disciplined, rigorous yet innovative core group would typify the characteristics of a successful MATE-CON team. Together, this dedicated team would not only focus on developing inspiring new products, but would also have the time and flexibility to focus on process improvement with the completion of each subsequent project. Their new paradigms would focus on 'transforming time into valuable insights' – providing their clients with interactive solutions rather than turning money into static deliverables such as a typed document or a one-time presentation. They would measure their performance on how inclusively, objectively and quickly their work can be accomplished, and on how well they applied innovation to meet the needs of the customer –providing solutions that fit within the performance and budgetary expectations but that are NOT the obvious designs that any other firm would have proposed. No longer would each team member be a separate expert specializing in one functional area: each, equivalent team member would hold the joint titles of "System Designer" and "Value Creator."

The approximate implementation timeframe would be about 3 months to the first full project utilizing MATE-CON in addition to ICE. It would take the completion of about 3 to 6 full projects in order to realize the full powers of process. Such a project would consume about 6 to 8 'man-months' of effort on the initial development and ramp-up of the MATE-CON system. Each subsequent project would consume approximately 20 – 30% more effort than a comparable ICE project due to the increased work associated with gathering utility preferences and exploring further reaches of the Tradespace than would otherwise have been done.

The potential return on that investment is phenomenal, however. Besides the increased team performance detailed in the preceding sections, the most important new asset is the attainment of the ultimate goals of concurrent engineering: <u>true, sustainable product and process innovation</u>. Only by fulfilling the farthest reaches of the PSI criteria can a CE team be equipped with the tools, processes and people necessary to create unbelievable innovations.

Although each one of the other CE processes has been used to create innovative new products, systemic barriers will inevitably prevent future teams from continued progress. The structures simply do not liberate team members from the traditional paradigms in the ways that MATE-CON can. These projects are either initialized with too narrow of a focus, do not give team members time to explore innovative new ideas, are not adequately provided with the leadership or authority needed, or fail to integrate the input from all stakeholders. MATE-CON completes the bridge to innovation by meeting and surpassing the important needs of Parallelization, Standardization and Integration. Teams that can harness the power and freedom of MATE-CON will have the confidence and the ability to design the future for all.

6.0 Expansion into other Functional or Business Processes (PROCESS)

Notes on Expansion:

- This is a whole new way of doing business
- It is not just one software tool intended to increase productivity of one or more teams.
- It cannot be applied indiscriminately to any program that is in trouble
- To succeed, courageous Leadership must be given the freedom and mandate to change the old ways.In order for the whole enterprise to benefit:
    - Team members need to work together as system designers, not merely as independent analysts
    - The team must learn as they go and be given the freedom to fail and then try again
    - They must then go and facilitate other groups through that process

- The enterprise must capture what the new groups learn and incorporate ideas into the next generation of product and process improvements

Role: Executive Management, Project Leader, all Team Members

Once the Integrated Concurrent Engineering Lab is well established, the process can begin to be integrated into other processes within the organization.

Specifically, the process can be used to improve the exchange of design preferences between the company and its customers. By asking customer representatives to participate in the design sessions, products and prices can be specifically tailored to meet exact needs. Additionally, the customer who participates will gain a deep understanding of the complexity of the product being produced, the inherent trades that result in the final architecture and price, and the depth to which the system designers examine each part of the system before proceeding with a proposed new design.

Downstream, the output of the design sessions should form the foundation of all detailed design work once a contract is awarded. Close coordination with the engineering, operations and supplier management organizations is therefore essential. Compatibility of processes as well as data formats must be ensured in order to make smooth transitions possible. Trust must be established so that detailed designers do not feel the need to start each analysis over in order to feel comfortable with the final results.

The expansion of the Integrated Concurrent Engineering concept from product design into other areas of a company will rest on the three enabling elements identified below:

1. Tradespace Exploration Tool (MATE-CON or similar)

2. ICE Techniques

3. Universal Knowledge System (UKS)*

These elements would be structured according to the diagram below with the goals of "Continuity and Universal Accessibility."

* The Universal Knowledge System (UKS)* concept is based on a dynamic expansion of many existing systems, including ICEMaker (currently used in ICE sessions), Xerox Docushare, and Oculus Technologies CO. In its current form, the ICEMaker Database is accessed by each of the ICE clients as a dynamic archive of alphanumeric parameters. In this approach, UKS becomes an interactive linking mechanism that collects, organizes and archives every bit of information for a particular program (CAD Files, Pictures,

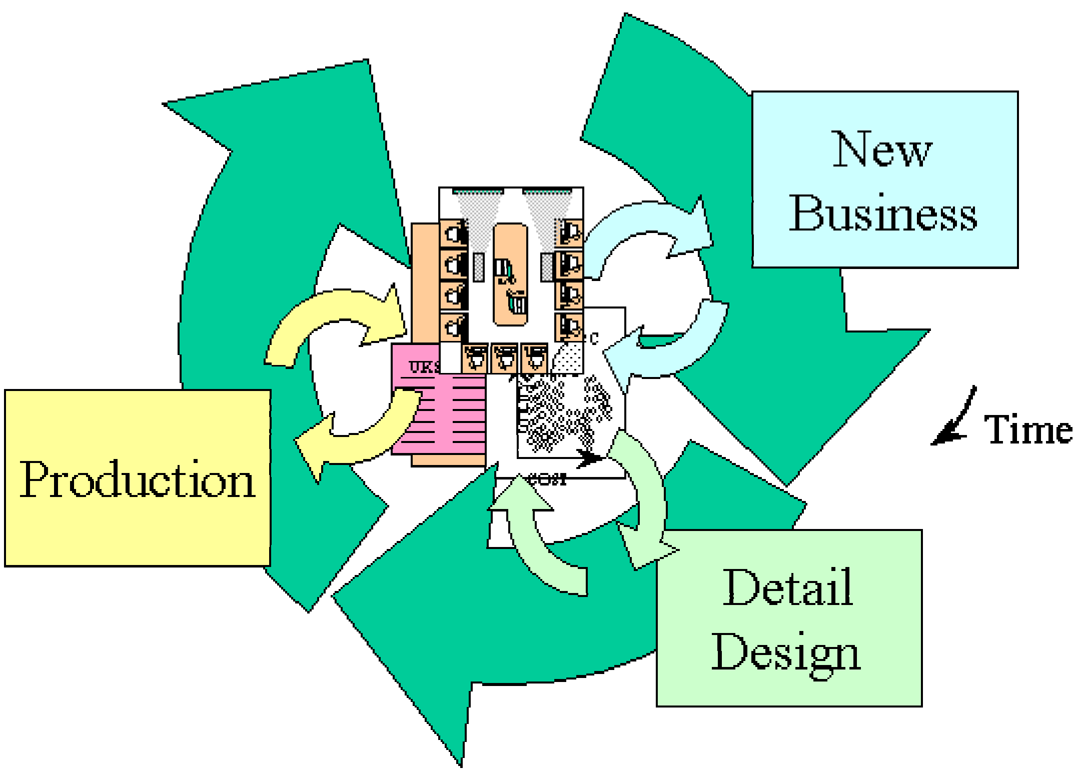


Figure 6-B-6: The ICEnterprise Lifecycle Model – The three enabling elements (an Integrated Concurrent Engineering Environment, use of a Trade Tool, and the Universal Knowledge System or UKS) play integral roles in each of the lifecycle phases.

Test Data, Unit Specs, Part Numbers, Performance Data, Subsystem Budgets, Labor Costs, Orders, Schedules, etc).Throughout each phase of the product lifecycle, the three enabling elements will play vital and complementary roles, leading to a smooth, controlled ascent through the three phases of the product lifecycle towards a completed, successful project as visualized in Figure 6-B-7.

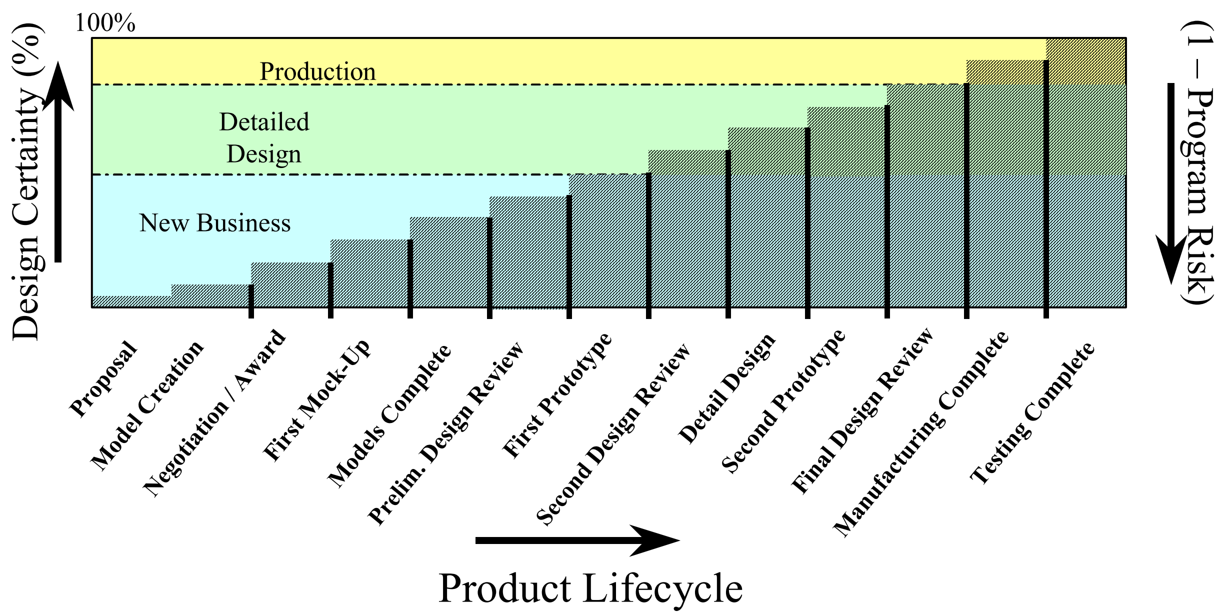


Figure 6-B-7: The ICEnterprise Product Lifecycle – The ICEnterprise systematically makes and communicates decisions as a product moves through its lifecycle phases. This increasing knowledge about the design and product replace risk in a corresponding manner.

6.1 Conceptual Design / New Business Phase

<u>Roles of the ICE Lab:</u>

- Tradespace Definition and Exploration
- Conceptual Design: Campaign Management, System Engineers and Subsystem Experts
- Generate Design-Review-Ready Output

<u>Roles of the Tradespace Exploration Plot:</u>

- Understand Customer requirements and system behavior
- Dynamically collaborate towards best-value solutions for Customer and Company

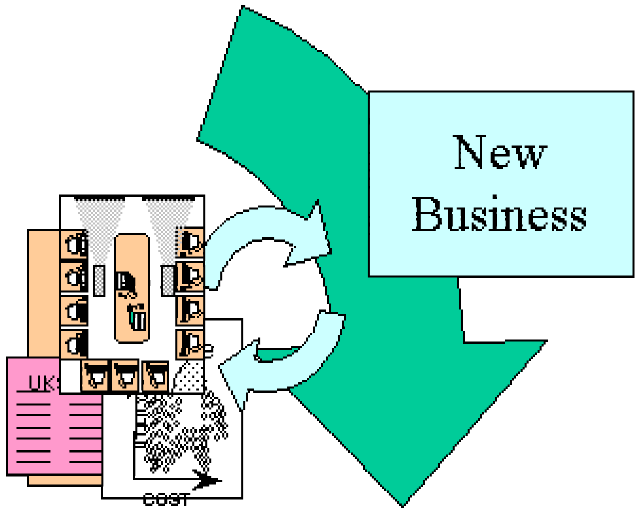


Figure 6-B-8: The ICEnterprise Lifecycle Model – New Business Phase

Roles of the Universal Knowledge System (UKS):

- Document the preferences, capabilities and decisions of all stakeholders
- Initialize the technical design and provide a record of key assumptions, risks and challenges**Detailed Design Phase:**

Roles of the ICE Lab:

- Program Reviews are held each day or week to integrate the latest information into the master design
- Generate PDR and CDR-ready outputRoles of the Tradespace Exploration Plot:

- Used primarily as a training tool to familiarize all personnel with the rationales for specific architecture choices
- Eliminates repetition of early analysis

- Tracks the progression of the design relative to the original baseline and Customer Preferences

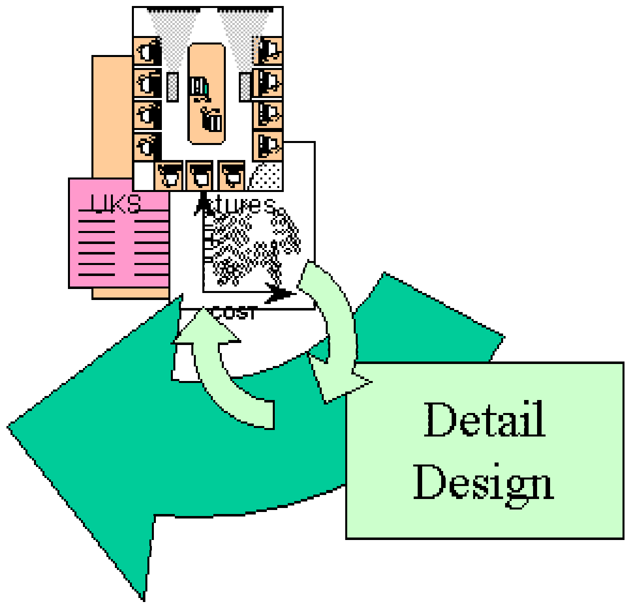


Figure 6-B-9: The ICEnterprise Lifecycle Model – Detail Design Phase

<u>Roles of the Universal Knowledge System (UKS)</u>:

- Subsystem ICE and DESIGN Labs feed into the Universal Knowledge System
- Teams can make decisions based on latest data or can plan when to work ("just-in-time" style)
- Alternative subsystem budgets and architectures are explored in the System ICE Lab and visible to all through the UKS
- Subsystem Labs perform the detailed design work and roll up their output into one top-level client which is stored in the UKS
    - ICE Labs utilize ICEMaker, which passes design parameters in a concurrent environment
    - DESIGN Labs utilize 3-D tools or alternative methods in a concurrent environment
- ALL data are stored and accessed through the UKS

6.3 Production Phase:

Roles of the ICE Lab:

- Program Reviews are held each day or week to integrate the latest information into the master design
- Actual values are substituted for calculated ones
- Discrepancies can be dispositioned accurately

Roles of the Tradespace Exploration Plot:

- Used primarily as a training tool to familiarize all personnel with the rationales for specific architecture choices
- Eliminates repetition of early analysis
- Tracks the progression of the design relative to the original baseline and Customer Preferences

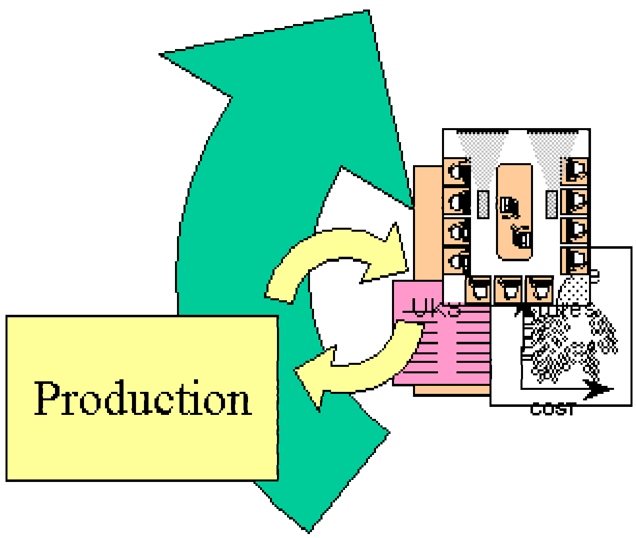


Figure 6-B-10: The ICEnterprise Lifecycle Model – Production Phase

Roles of the UKS:

- Remains the central data clearinghouse
- Inconsistencies are avoided
- Data transmission to Customers and Users is seamless

As the program moves through the different phases, the team builds upon the common core of personnel and knowledge as decisions are made and material begins to move. Each successive module of knowledge, functionality and infrastructure can be integrated seamlessly into the existing enterprise.

- Training can be accomplished rapidly using ICE Laboratories and interactive models.
- Team members can make decisions based on the latest information regardless of their location or function.
- Detail design labs can spring up as needed to tackle difficult problems.
- Discrepancies or supply chain interruptions can be dispositioned efficiently and effectively based on real-time system analysis.

Changes in market conditions and customer preferences can be translated immediately into decisive action. Logistically speaking, this proposal would require the complete commitment of top management. All team members would have to understand the new approach, how to create and access the new tools and techniques, and how their specific roles would need to be adapted to harness the power of the new system.

There are a number of experts who could help facilitate the transition of an ICE Team, but for the most part, research and experience has shown that upon exposure to these concepts, and with the necessary leadership, the required tools and processes emerge very naturally from the teams themselves.

In terms of investment, nearly all of this work will be done regardless of the system design approach. However, once the work is completed in the traditional sense, and team members move on, all of the tacit knowledge will leave with them, and the static system they create will be left to deal with the challenges that no one could have predicted.

7.0 Alternate Applications of ICE and MATE-CON

Although MATE-CON was initially developed as a front-end, conceptual design process, its tools and techniques are widely applicable. The Table below can be used to understand the scope and impact of work required for applying ICE and MATE-Con to various design scenarios.

Scope and Impact of ICE and MATE-CON Relative to Type of Design			
Design Type:	**Tradespace (MATE-CON system architecture)**	**ICE Worksheets / Models / Process (modules within the MATE-CON system architecture)**	**Customer Preferences (MATE-CON Utility Curves)**
Radical New Architecture or New Technology	Entirely New	Almost All New	Almost All New
New Design Architecture, Existing Technology	Almost All New	Almost All Existing	Almost All New
Standard Design - "Applications Engineering"	Almost All Existing	Almost All Existing	Almost All New
Detail Design	Use Existing	Some New	Use Existing
Disposition of Under-performing Subsystems	Use Existing	Use Existing	Use Existing

Recent research has focused on simplifying the utility interview that is required to perform a MATE-CON analysis in order to make the process more widely accessible (Spaulding, 2003), (Stagney and Guerrero, 2003). In addition, the process can be modified in order to apply it to a number of different business and engineering scenarios. The following are a few examples of potential problem-solving methodologies formulated from MATE-CON by the author:

7.1.1 System-Immersion Workshop

<u>Purpose:</u> The goal of this exercise would be to create among a project team a concrete, universal understanding of the most important aspects of your system. The output would be a unified mental and electronic model of the potential design solutions. Each team member would come away rejuvenated and with a renewed sense of direction and clarity of purpose.

<u>Needs Addressed:</u> Fundamentally, a team consists of experienced and talented individuals who each bring a unique and important perspective to the challenge at hand. As with any group of successful, strong-willed people, discussions of seemingly universal concepts or technical issues can be time-consuming and inefficient. By human nature, each person's pre-conceived notions tend to bias their points as well as their interpretations of others ideas. Often, what one person believes to be a clear decision is seen by another as a strong discussion with important questions still to be answered. As options are brainstormed, they are not always recorded or traded against each other in a systematic fashion. The potential solutions to an exciting new problem are nearly boundless, yet teams time and again limit their potential before they even begin – their old paradigms gently herding them back into familiar and safe territory.

Approach / Investments / Benefits: Depending on the level of detail desired and the size of the team, this concept would take the form of a one or two week full-time workshop – preferably in a remote or insulated venue. Facilitators would guide the team through a process of deconstruction, objectification, reconstruction, and systematic analysis. As they generated a Tradespace Exploration Model, the team would work together to gain a common understanding of the most influential design variables and their inter-relationships. They would identify opportunities for radical innovations and be able to weigh highly risky propositions against safe conventional approaches.

7.1.2 Targeted, Deep-Dive Study

Purpose: The objective of this option would be to examine a particularly important or stubborn aspect of a system design that could benefit from an objective external analysis.

Needs Addressed: As mentioned above, when teams make difficult decisions, it often helps to work through a structured process that can bring to light many of the underlying assumptions that may be unconsciously influencing the process. Having a subset, parallel effort can often add tremendous value to a group that may become fixated on certain elements of a problem. In addition, access to a powerful custom analytic tool can enable highly experienced team members to hone in on key characteristics of a design very efficiently.

Approach / Investments / Benefits: A small team of 3 to 5 people would be broken from the main group or assigned from outside the immediate organization. Working full time for two to four weeks, this team would create a low-resolution Tradespace and ICE Model. Once validated, the main team could hold a series of concurrent-engineering-style brainstorming sessions. They could pose a sequence of 'what-if' scenarios and explore the potential outcomes, system architectures and value propositions. In addition, they could uncover some of the risks associated with particular design options and install robust countermeasures. Although the final decisions would most likely be made in the traditional meeting fashion, this objective discovery process could significantly enhance the quality and depth of the outcome.

7.1.3 Team Resource

Purpose: This option is intended to be a low-cost, low-risk alternative to some of the other ideas presented in this document.

Needs Addressed: Again, as stated above, a team may experience many of the patterns of group dynamics that are commonly observed. Sometimes, all a team needs is exposure to an innovative new technique to refocus their efforts or generate new ideas of their own.

Approach / Investments / Benefits: This concept would take shape as a one-day interactive presentation given by experienced ICE practitioners. It would examine, in 'testimonial' format, the fundamentals of the ICE and Tradespace Exploration processes. Team members could then participate in a live exploration of an existing model as a means of understanding the potential capabilities and applications beyond what I have proposed here.

7.1.4 Long-Term Option: Enterprise Design Technique

Purpose: The potential benefits of a well-designed, robust and flexible Project enterprise will have lasting impacts. This concept would approach the design of an entire Project Enterprise (i.e. Joint Strike Fighter, etc) (technical and business) with a completely new technique.

Needs Addressed: As described in the previous chapters, there are significant losses associated with the traditional meet/work/meet approach to system design. No matter how experienced and talented the team members are, there will inevitably be information losses and rework. These concepts unite a team's knowledge base, facilitate collaboration and ensure universal assumptions and value propositions.

Most significantly, large new products face extremely unstable market futures. Use of the ICE and MATE-CON techniques provide an extremely innovative approach to dealing with risk and uncertainty. Not only do the models produced by these design methods provide powerful insights into potential scenarios, but they also create dynamic models that can be analyzed, updated and shared by all team members in order to understand the strengths and weaknesses of both past and present decisions.

Approach / Investments / Benefits: This proposal would involve the entire enterprise team, for example (marketing, design, supply chain, government, military, etc). The overall structure would involve the use of a MATE-CON team to design the entire enterprise rather than one particular product. The attributes of such a system could be its strategic advantages, global reach, market shares, cost structures, logistics networks, tangible assets, etc. The objective would be to maximize sustainable profitability of the enterprise subject to the volatility of the global business cycle, natural disasters, or changes in consumer preferences. This is a new approach to the clean-slate design of a new enterprise.

7.1.5 Long-Term Option: System Design Technique

This proposal would apply the concepts presented above in the "Enterprise Design Technique" to the design of the Supply Chain system only.

7.1.6 Long-Term Option: Dynamic System Model

Purpose: This proposal would be essentially the same as the "Targeted Deep Dive" proposed above but would apply to a much larger challenge impacting an entire enterprise effort. It could be applied to the study of system shocks, scenario planning, costing initiatives, etc.

Needs Addressed: See above.

Approach / Investments / Benefits: Essentially a full team of approximately 15 personnel would venture off on their own to create in-depth Tradespace Exploration and ICE models for the problem at hand. They could work for 3 to 6 months on an issue and then interact with other members of the enterprise. The dynamic models they create could be used throughout the enterprise for a wide variety of purposes including cost negotiations with customers or suppliers, etc.

7.1.7 Long-Term Option: Standing Tiger Team

Purpose: The purpose of this concept would be to have a team of personnel fully trained in ICE and Tradespace Exploration 'on-call' to attack any important issue that is holding up the rest of a project team.

Needs Addressed: In a major new development program, there are inevitable technical and business bottlenecks that can prevent entire programs from moving forward.

Approach / Investments / Benefits: A team of 5 to 15 selected key stakeholders could be sent for a one or two-week ICE / Tradespace Exploration workshop. They would work with experts to create their own unique models (could be a real problem or a hypothetical issue) and analysis. Once trained, they could then be called in at any time by top management to address an urgent issue and come up with robust, innovative solutions.

7.1.8 Long-Term Option: Customer Input Device

Purpose: This idea is intended to harness the powers of the Tradespace Exploration technique with regards to decision-maker preferences.

Needs Addressed: This concept will enable a team to quantify the current needs and future desires of a wide variety of customers. In the traditional approach, teams of marketing representatives who each have very close relationships with various Boeing customers approach their contacts and attempt to elicit the preferences and business objectives of each customer. This knowledge is then codified and transferred to the design team who must compile the inputs from a wide variety of sources (each with different backgrounds, personal styles and personal opinions) then interpret the data they receive. Often, these explicit communications are attempting to describe tacit knowledge (look and feel of the product, etc). Additionally, each potential customer is in a state of extreme competition with the other customers and thus does not want rivals to obtain the same competitive advantages that they are striving to achieve.

Approach / Investments / Benefits: This option would involve the creation of a universal Tradespace Exploration model that could then be analyzed according to the unique attributes and preferences of each customer. A well-designed MATE-CON system allows customer preferences to be absorbed readily into any analysis – here, the model is purposely re-created for each customer, and competing architectures are examined to understand the common elements, and which elements should be purposely left for customization at a later date. A team of approximately 15 members would create the models, and then teams of 3 to 5 would conduct interviews with each customer to determine their most important attributes and the corresponding utility functions.

7.1.9 Supplier Input Device

This proposal would be very similar to the one described above, however would be used to communicate with and integrate suppliers in to an enterprise. Instead of polling for customer preferences, teams would pull key suppliers into the ICE and Tradespace Exploration processes. In those concurrent sessions, suppliers could understand how crucial they are to the entire operation, and could suggest improvements in the system based on this new perspective.

Section 6-C: Clean Slate Design of an ICEnterprise

The creation of a brand new ICEnterprise will be a highly entrepreneurial undertaking. Most likely, the first ICEnterprises will be started by highly experienced and respected engineers or project managers who have become frustrated and limited by the constraints of large bureaucratic organizations. They could initiate a new organization by obtaining money from private investors, from a forward-looking customer who is seeking to spark radical cost savings and dramatically improved performance, or from a large established corporation who is also looking to break traditional paradigms (in an isolated experiment). In the latter case, the name of the parent company could help the new enterprise to overcome initial skepticism from some conservative customers.

The entrepreneur in order to determine the potential products and or services that the new venture will provide, and the current market prices for these items should complete a thorough business analysis. After selecting the industry that will be serviced (i.e. small planes, cars, boats, computers, software, construction, etc), and the approximate products that will be initially produced, the new ICEnterprise should then proceed through the following phases:

Phases of a New ICEnterprise		
Phase 1	Approx. 2 to 4 months	Formation of Star Team: The most important part of a new ICEnterprise will be the star people who populate the first team. The team leader (which could be the entrepreneur) will seek out a multi-disciplinary team of talented and open-minded individuals from companies throughout the industry. They must not only be computer-savvy and intellectually capable, but experienced with hardware because the first team may be required to not only design, but build and test prototypes or initial production units. Each new team member will be required to quit their old jobs in return for a one-year contract to help develop the ICEnterprise operating systems and initial products. New team members will be offered the same salary that they are currently earning, but will also receive a small amount of equity in the new venture as well as all moving expenses associated with relocating to the site of the new enterprise. All team members will be required to live within 10 miles of the new headquarters in order to build a sense of community and shared responsiveness. The team leader will locate an appropriate site for the ICEnterprise and hire one highly skilled administrative assistant for the team who is a strong writer and capable of doing web publishing and other key organizational tasks.

Phases of a New ICEnterprise		
Phase 2	Aprrox 6 months	<u>ICEnterprise Capability Development:</u> The team will initially split their time 3 ways (they will all work on the same tasks on the same days). All need to be involved in all activities otherwise the team may not have buy-in later on when things really get going, and to build momentum and camaraderie in order to eliminate unnecessary delays: Mondays and Wednesdays: Identify target jobs – should be jobs that deliver actual hardware that the team thinks they can design and build first unit(s) within reasonable time, and is something they are all very passionate about. Target to deliver at 20 to 40% less cost than other bidders. Tuesdays and half of Thursdays: Identify sources – once the team receives a contract, they will need to rapidly access other talents. They need to have a full directory of mental and physical assets they can call at any time. The team can contact past colleagues for analytic help, job shops for prototyping or parts, other standard industry suppliers for common parts, etc. They will need to establish an understanding with these businesses and people so that they can access their ideas and input early in the design phase in order to design a low-cost, manufacturable product. All suppliers will be hired on a contract basis only. The team will be willing to pay premium prices for expedited deliveries or full-time dedicated support staff. Half of Thursdays and Fridays: Develop ICE process capabilities – just learn about ICE, visit other labs, do norms, etc. Depending on the industry or product, the team may not yet be able to develop an N-squared diagram or models because they don't know the specifics of a particular product challenge. The team can however build an information architecture so that all will have instant access to all design information and the ability to trace all requirements and verify they are achieved.

Phases of a New ICEnterprise		
Phase 3	Approx 1 to 6 months	Active Pursuit of Business: As the team becomes more confident in their own ICE process and their base of supplier capabilities, they can shift their efforts to 3 then 4 days a week on proposal pursuit. After selecting the final 2 or 3 targets, they can build ICE models, a lab, and write proposals. The team will be able to construct integrated cost and schedule models because they already know the capabilities of their potential supplier base (but they may have to invite key suppliers to participate in design sessions). There will inevitably be down time between proposals and selections – that's ok – the team can continue to build capabilities and do practice studies, build prototypes etc. They should maintain very intimate contact with customers so efforts are not wasted and the team does not become fixated on designs that are not desirable to the customer.
Phase 4	Approx 1 to 2 years	Contract Award and Execution: Once the initial project is awarded to the ICEnterprise, the star team moves into action. It completes the ICE models, performs tradespace analyses, and works with the customer and its suppliers to select the final architecture. The team can then construct prototypes, perform testing, and initiate the manufacturing process in order to deliver high-performing products on-time and under-budget.

Estimated Startup Budget of an ICEnterprise (first year of operations:

Salaries / Benefits:	
Team Leader:	$100,000
Team Members (Avg. $80,000 x 15):	$1,200,000
Administrative Assistant:	$60,000
Relocation (Avg. $15,000 x 17):	$225,000
Healthcare ($6,000 x 17):	$102,000
Payroll Taxes (12%):	$163,200
Subtotal:	**$1,880,200**
Facilities, etc:	
Rent ($5,000 x 12 months):	$60,000
Maintenance / Utilities ($4,000 x 12 months):	$48,000
Computers / Software ($5,000 x 17 users):	$85,000
Office Furniture / Equipment:	$20,000
Consultants (IT, accountants, legal, etc):	$100,000
Travel ($5,000 x 17 team members):	$85,000
Insurance:	$25,000
Fees to (potential) suppliers:	$75,000
Subtotal:	**$498,000**
Total Estimated First Year Expenses:	**$2,378,200**

NOTE: The above-itemized expenses yield a calculated "overhead rate" of 198%. In other words, the ICEnterprise incurs $39.27 in expenses for each hour of productive employment of the 15 team members (who are each paid $40 per hour). Aside from the fact that the ICEnterprise team members will be vastly more productive than their traditional counterparts, this rate compares to rates of 300% to nearly 400% in large bureaucratic firms.

Chapter 7: Conclusions

Section 7-A: Summary of Findings

In chapter 1, it was argued that large corporations have not changed their basic problem-solving approach in over 100 years. The decomposition method still reigns as the foundation upon which nearly all modern projects and organizations are built. Regardless of the specific product, the fundamental approach is the following:

- Highly experienced, well-respected engineers or managers formulate a new product design concept.
- The proposed design is methodically broken down into sets and subsets of small tasks, and each is assigned to a specialist or team of specialists.
- Managers and engineers then sum the results up into a final product.

History has shown, however, that the efficiencies initially gained by specialization of labor have over time become masked by the complexities of managing scores of specialists and by the sub-optimization of designs that results from the organizational insulation between the specialists.

Managers have not sat idle as these inefficiencies became more apparent. Concurrent Engineering (CE) was a general strategy developed to make decomposition more effective by breaking down the organizational and schedule monuments that left specialists to toil in isolation from each other. In Chapter 2, a number of the most widely practiced CE processes were presented and analyzed. Each were examined in the context of an analytic framework that helped to capture the full scope of the Technical, People and Process Questions.

As measured by the PSI framework, Chapter 3 described how the Integrated Concurrent Engineering Process (ICE) – in tandem with the MATE process (Multi-Attribute Tradespace Exploration) to form MATE-CON – presents a new hope for the concurrent engineering movement. If implemented as envisioned, MATE-CON could strike an efficient balance between strong and weak systems engineering philosophies and finally bring about an effective paradigm shift away from the decomposition method.

Chapter 4 explored the implementation of the ICE and MATE-CON processes through a detailed case study of the RTCE (Real Time Concurrent Engineering) Team. The team was able to bring about substantial changes in the way that problems were decomposed and the techniques that allowed specialists to work together. Unfortunately, the RTCE team was innovating in the midst of an organization that resisted the new approach because it did not fit into the existing paradigms:

- It could not be measured using a traditional ROI metric
- It created conflicts between specialists who technically reported to functional managers but knew that their best contributions could be made as generalists who worked for the team
- It did not adequately integrate the skills and needs of all the specialists and thus became politicized during struggles for the limited amount of development funding that was available
- Those who were on the team could see how the RTCE process could revolutionize the way their company did business, while those who were not on the team saw it as merely another management fad

As a group, as currently implemented in industry, the 7 CE processes presented (including ICE and MATE-CON) are merely incremental improvements to the decomposition method. Because the corporations in which they are employed are based so solidly in the entrenched approach, the addition of any number or form of the CE processes can only bring about temporary improvements that are quickly overcome by the natural progression of product and process complexities. In addition, the accompanying re-organizations that are periodically announced only serve to compound the problem – the fact that rigid organizational boundaries exist at all is a sign that the decomposition paradigm is alive and well.

Thus, Chapter 5 laid out the author's vision for the Integrated Concurrent Enterprise – its guiding principles, as well as structural and organizational attributes. The ICEnterprise is based on the highly flexible project-based organizational model of

Hollywood movie studios, where ach new project follows a "composition" process as opposed to the decomposition process employed by most traditional organizations. In the ICEnterprise, each new team is uniquely composed from the available pool of talent and suppliers. In a traditional corporation, a new project enters the company and is decomposed into a number of tasks that are then assigned to functional departments – each new project is forced to fit the existing organization. In contrast, in the ICEnterprise, a miniature organization is custom-built to fit each new project.

An ICEnterprises star system attracts and rewards the hardest working and most innovative in the world – regardless of seniority or status. Its industry-wide practices promote the formation of a critical mass of talent and resources that are employed at market prices rather than through a historical entitlement scheme. The power that an ICEnterprise will have over traditional competitors will be absolutely overwhelming – speed, flexibility, affordability, innovation and peer pressure. Once an ICEnterprise establishes itself, decomposition-based organizations will not be able to stop the tidal wave of talented and experienced people who will flock to the newfound freedoms and personal rewards of the pioneering venture or to one of their own design.

The last chapter contained a detailed implementation roadmap for building an Integrated Concurrent Enterprise. For entrepreneurs and intrapreneurs alike, the first few steps toward an ICEnterprise will be questioned and challenged by those who have been taught and practiced decomposition their entire lives. Many will say that star systems are unfair and will breed corruption. Others will argue that the implied lack of job security will wreak havoc on families and personal finances. Still others may feel that project-based companies already exist and haven't proven to be more efficient or profitable than other business models. Reading through current headlines of massive corporate accounting frauds, defense contractors that follow a binge-and-purge cycle of hiring's and layoffs, and business gurus that appear and disappear, it should be easy for the reader to realize that human flaws can taint any system. The challenge will be to build an enterprise that rewards initiative, integrity and openness.

Finally, and most importantly the critics of the ICEnterprise will miss its greatest strength – the fact that it empowers great people to reach unforeseen heights in whatever manner they see fit. That all of the CE processes presented can claim just as many failures as they can success is a testament to the fact that each new project is unique in its technology, people and processes. No standard approach or best practice can ever be universally implemented – what creates unprecedented success to one team can lead to complete failure for another. Until an enterprise can truly trust its people to follow their talents, experience and intuition – the very skills it pays them for – it will never achieve sustained success.

The leaders of the ICEnterprises of the future will be challenged to extend that trust time and again. As in Hollywood, the greatest stars are often measured by their abilities to learn from the ashes of failure the lessons of future success.

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