Multidisciplinary Design Problem Solving on Product Development Teams

by **Joshua I. Bernstein**

Bachelor of Science, Mechanical Engineering
The Johns Hopkins University, 1996

Master of Engineering, Aeronautics and Astronautics
Massachusetts Institute of Technology, 1997

Master of Science, Technology and Policy
Massachusetts Institute of Technology, 1998

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Signature of Author ______________________________
Technology, Management, and Policy
September 15, 2000

Certified by ______________________________
Thomas J. Allen
Howard W. Johnson Professor of Management, Sloan School of Management

Certified by ______________________________
Timothy G. Gutowski
Professor, Department of Mechanical Engineering

Certified by ______________________________
Warren P. Seering
Professor, Department of Mechanical Engineering

Certified by ______________________________
J. Thomas Shields, III
Center for Technology, Policy and Industrial Development

Certified by ______________________________
Joyce M. Warmkessel
Senior Lecturer, Department of Aeronautics and Astronautics

Accepted by ______________________________
Daniel E. Hastings
Chairman, Technology, Management, and Policy Program

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Joshua I. Bernstein

Submitted to the Technology, Management, and Policy Program on September 15, 2000 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Technology, Management, and Policy

Abstract

This investigation, conducted under the auspices of the Lean Aerospace Initiative (LAI), studied how engineers from different specialties interpret and communicate about technical design problems while working on product development teams. Data was collected on 98 cases via interviews with engineers at LAI member companies. For approximately one-third of the cases, two engineers with different backgrounds were interviewed, allowing comparisons to be made between their descriptions of the problems under study. For the remaining cases, one interview was conducted per case.

The most important finding of this study was that engineers from different specialties do interpret the same problem differently. Specifically, two engineers were likely to evaluate the benefits or drawbacks of a potential solution using different sets of criteria. Thus, some design disputes were the result not of mutually exclusive needs but of a failure to recognize the different ways in which engineers were evaluating solutions to the problem. Furthermore, data collected during this study illustrated that in some cases these differences were the result of engineers addressing related, but unique problems. Therefore, a solution to one engineer's problem often created a new problem for another engineer on the team.

A second conclusion of this study was that how design tools were used had a greater impact on a team's problem solving abilities than what tool was used. In this context, design tools included objects such as real or "virtual" prototypes as well as processes like simulations and tests. The results of this investigation suggested that such tools offered their greatest benefits when they were used in a participatory fashion in which a large fraction of a team shared in their use. Additionally, the more elements of a problem's context that were captured in a design tool, the greater its utility. Under such conditions, team members were able to create a shared evaluation system to judge potential solutions to the problem they were confronting, thereby facilitating problem resolution.

Based on these results, the traditional model of engineering communication derived from the information processing framework requires modification. The information processing model assumes that individuals have a shared understanding of meaning when they communicate. This study, however, suggests that such shared understandings do not exist in advance, but are instead created as part of the communication process. While the information processing model may work well to explain communication patterns at a high level or within a well-established group, a model that accounts for the active and dynamic creation of shared meaning is more appropriate at a detailed level.

Thesis advisor:
Thomas J. Allen
Howard W. Johnson Professor of Management
Sloan School of Management

Doctoral committee:
Timothy G. Gutowski
Professor
Department of Mechanical Engineering

Warren P. Seering
Professor
Department of Mechanical Engineering

J. Thomas Shields, III
Lean Aerospace Initiative Program Manager
Center for Technology, Policy, and Industrial Development

Joyce M. Warmkessel
Senior Lecturer
Department of Aeronautics and Astronautics

Program chair:
Daniel E. Hastings
Professor and Chair
Technology and Policy Program

MULTIDISCIPLINARY DESIGN PROBLEM SOLVING ON PRODUCT DEVELOPMENT TEAMS

Joshua I. Bernstein
Lean Aerospace Initiative
Massachusetts Institute of Technology

Executive Summary

This investigation, conducted under the auspices of the Lean Aerospace Initiative (LAI), studied how engineers from different specialties interpreted and communicated about technical design problems while working on product development teams. Specifically, the study was aimed at improving our understanding of how engineers can best use design tools, such as computer aided design (CAD), prototypes, and computer simulations, to improve product development processes.

Data for this study was gathered during visits to corporate members of the Lean Aerospace Initiative consortium. Engineers with recent experience on product development teams were interviewed for thirty minutes to one hour using a critical-instant interview approach. Depending on their time and willingness to participate, each interviewee described one to two cases of technical problem solving on product development teams. Overall, ninety-six interviews were conducted for this research study, yielding a total of ninety-eight cases. For twenty-six of these cases, a second perspective was obtained through a follow-up interview with another team member.

Data was analyzed using a combination of quantitative and qualitative techniques. In cases for which two interviews were conducted, engineers were asked to provide a list of the criteria they used to evaluate a potential solution's benefits or drawbacks. Comparing the lists created

by each pair facilitated the development of two quantitative metrics, the “unique criteria ratio” and the “unique problem ratio”, to measure the extent to which the engineers’ interpretations varied. Additionally, for all cases engineers were asked to rate their satisfaction with the solution and to estimate the solution’s impact on the product’s performance and cost and the project’s schedule. These data were quantified using seven-point Likert scales. Finally, the quantitative analysis was supplemented by the case descriptions gathered during the interviews.

Several key conclusions were drawn from this investigation. First, engineers from different backgrounds do think differently about the same problem. This notion was clearly illustrated in the cases for which paired data was collected. When asked to list the criteria they used to evaluate the benefits or drawbacks to potential solutions, engineers from different backgrounds often cited different issues. Furthermore, looking at how the engineers described their problems more clearly revealed the origins of these differences: the engineers were often solving *different problems*.

For example, one case dealt with the repair of a fatigue crack in an aircraft part. One interviewee for the case was the design engineer. He discussed the problem in terms of stopping the spread of the crack and the crack’s impact on the aircraft’s performance. The second interviewee was the tool designer. He was responsible for developing a tool that could be used in the field to repair the crack and talked about how a human being might be able to gain access to the crack and how much space was available to move a tool. Thus, to some extent the engineers were not even solving the same problem. The engineer framed the issue in terms of the crack’s impact on performance; in contrast, the tool designer framed the problem in terms of a human reaching the crack. Similar issues were identified in many of the other cases.

Therefore, the data indicate that engineers from different backgrounds do think about and analyze the same problem in different ways.

Given these differences, methods are required that facilitate the creation of solutions that are mutually beneficial from multiple engineering perspectives. Based on the data collected during this study, one of the most effective methods was the use of tests. As defined for this investigation, a test may be conducted on a completed or prototype part or may be conducted using computer simulations. The important feature is that a design concept is developed and then subjected to an experiment that reveals some aspect of its performance. Furthermore, as defined in this study, to qualify as a "test," either the team as a whole had to agree to conduct the experiment or the team as a whole had to witness its results.

Testing was a common theme among the solution processes of many cases. The importance and effectiveness of testing appeared to lay in several factors. First, the engineers had to agree to conduct the test. Further, in agreeing to the test, the engineers agreed to a standard of evaluation. Since the test determined what data could be collected, and the type of data determined what aspects of a potential solution could be evaluated, agreeing on what test to do allowed the engineers to first debate and then agree to a set of attributes that were mutually important for a solution. Second, once the test was conducted, the resulting data provided a powerful counter to any theoretical or philosophical arguments that had been taking place over the problem. A common remark was, "The data said x, so that's what we went with."

An important caveat, however, was that all of the conflicting parties had to be involved in the decision about what test to conduct. In several cases, this participation did not exist, and the tests were not as decisive. Under such circumstances, the engineers from the excluded group were able to say, "I don't believe the data," implying that the test was not properly conducted.

Such problems reinforced the notion discussed above, namely, that testing is only an effective integration tool when it facilitates the discussion over how potential solutions should be evaluated.

These results also shed additional light on the concept of "boundary objects" (e.g., an artifact such as a drawing, part, etc., that is shared between individuals from different groups or specialties). In some sense, the results from a test can be viewed as a boundary object. However, it is not the sharing of the results alone that was important. What was also important was the consensus that was initially required to *create* the object. When that agreement was lacking, the utility of the object was reduced. Thus, one can propose two scenarios. In the first, a boundary object is brought to a meeting by one side of a design dispute so that it can prove its point. Based on the results of this study, one would expect such a presentation to be met with considerable resistance. In the second scenario, the disputing groups as a whole first agree that it would be worthwhile to create an object. One would then predict that the sharing of that object would be an effective mechanism to help resolve the dispute. Therefore, this study has provided an additional level of guidance for using boundary objects.

This study also found that well-known, shared team objectives and team co-location were positively correlated with team member satisfaction and product and project performance. The significance of shared objectives reinforces the argument that teams need to establish a shared system of evaluation. When project goals were well known to the team, its members tended to evaluate design problems -- and their potential solutions -- more similarly than when such goals were not present. Therefore, team members were able to reach a consensus more easily about how to solve the problem. Similarly, co-located teams were able to meet regularly and easily, allowing team members to get to know each other personally and to learn about each other's technical concerns. This increased understanding and awareness then facilitated effective problem solving.

Importantly, the results also revealed that teams using frequent face-to-face meetings instead of co-location reported lower satisfaction and less positive impacts on product and project performance. Thus, co-location appeared to have significant benefits that could not be matched simply by attempting to hold frequent meetings.

Finally, the results of this research lend support to the concept of design-build-test cycles. This model of the product development process suggests that engineers should work in short, rapid cycles in which a design concept is first generated, and then a real or virtual prototype created and tested. Proponents of this model usually cite its potential to reduce technical uncertainty as its greatest benefit. This study, however, also suggests that teams using the design-build-test approach should be more effective from a social standpoint as well. Thus, future investigations might explore how well teams using design-build-test approaches solved problems compared to those not using such an approach.

In summary, this study has clearly illustrated that engineers from different specialties or backgrounds interpret and evaluate design problems differently. Furthermore, these differences in interpretation are often due to the fact that the engineers are actually solving related, but physically different problems. Therefore, processes are required that facilitate the creation of a shared interpretation of, or evaluation system for, the design problem. The results of this investigation have indicated that the design and execution of tests, either real or "virtual," are an effective means of incorporating such processes into a product development project.

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This research project based its data collection approach on interviewing product developers actively engaged in the practice of creating new products. Two types of individuals, therefore, were critical to this project's success: points of contact at the participating companies and the interviewees. The points of contact provided me a vital link between my research needs and the means to fulfill those needs. Without their time and effort, this project would never have begun. Furthermore, I thank the many engineers, managers, and manufacturing personnel who were willing to meet with me to discuss their experiences. In order to protect the confidentiality of the companies that participated in this study, these many individuals must remain nameless. Nonetheless, I thank them for their efforts.

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1. INTRODUCTION

1.1. *Motivation*

Developing a product that can succeed in the market is a task fraught with a diverse set of challenges. Thus, companies are continuously seeking to improve their product development capabilities, whether it be better predicting market needs or enhancing their products' technical performance. As will be discussed, a variety of studies have shown that a key element of developing successful products is the ability to successfully integrate the many technical views and needs represented by different elements of a product development organization. The better these groups can work together, the better the products they will produce.

To that end, this research project aimed to improve the ability of product development organizations to integrate their technical disciplines to deliver successful products. This broad issue was studied in detail by investigating how multidisciplinary product development teams solved specific design problems during the course of larger development efforts. Since this project was sponsored by the Lean Aerospace Initiative (LAI), it has endeavored to investigate issues of special concern to the development of large, complex systems such as those developed for the United States Air Force.

As this paper will argue, successfully integrating a product requires that the many diverse subgroups within an organization effectively communicate with one another. Thus, improving a company's ability to integrate its products requires improving its ability to communicate. The goal of this project was to improve our understanding of what makes for effective communication between specialty groups, and, with that understanding, improve a company's ability to deliver well-integrated products to the market place.

1.2. Project History and Evolution

The Lean Aerospace Initiative's mission is "[t]o enable fundamental change within industry and government operations that supports the continuing transformation of the US aerospace enterprise towards providing aerospace systems offering best life-cycle value" (Murman, 2000). To support that goal, this project was originally intended to investigate the transition of a product development project from the design phase to the manufacturing phase of the development process. This initial objective was based a variety of studies and expert opinion within the LAI community that suggested that this transition process progressed far less smoothly in Department of Defense (DOD) projects than in comparable commercial projects (see, for example, United States Air Force, Engineering Directorate, 1998; United States General Accounting Office, 1998). DOD products were confronting significant manufacturing and performance problems, resulting in increased development costs and delayed schedules.

Preliminary investigations, however, rapidly shifted the project's focus. Industry feedback, acquired during discussion sessions at LAI team meetings and conferences during 1998, suggested that the "transition point" as imagined for the study was not nearly as well-defined in practice as initially thought. Furthermore, industry representatives noted that the concept of a well-defined transition between phases was not consistent with the integrated product and process development (IPPD) methods they were attempting to implement. Instead, manufacturing input was being provided throughout the design phases of new products, even during early conceptual development. This more continuous back-and-forth communication pattern was inconsistent with the notion of a clearly defined transition point.

Several other concepts suggested that the transition point itself was not the proper place to solve the problems being seen at the shift from design to manufacturing. First, several studies have indicated that manufacturing quality is a function of design quality (Clark and Fujimoto, 1991; Wheelwright and Clark, 1992; Womack et al, 1991). That is, products that are designed with manufacturing issues taken into account *in the design itself* are less likely to have manufacturing problems when they begin production. Concepts such as design for manufacturing and design for assembly (Boothroyd and Dewhurst, 1994; Ulrich and Eppinger, 1995) have been developed specifically in response to this realization. Thus, if manufacturing quality is driven by the design process, no amount of tinkering with the transition point will be able to fix the problems that were designed into a product earlier in its development. This thinking is consistent with systems theory, which notes that the sources of problems are often displaced from the point at which the problem is revealed (Senge, 1990; Sterman, 2000).

If the transition point was not the proper focus of study, and previous work had already developed concepts such as design for manufacturing and assembly, the question then became, "What is preventing manufacturing knowledge from being incorporated into the design of new DOD products?" With the problem now framed in this context, the focus of this study gradually shifted to understanding how engineers from different specialty groups (such as design and manufacturing) work together to solve a design problem that requires knowledge from several different perspectives. This work represents the investigation undertaken to understand these issues.

1.3. Fit with Lean Frameworks

This research fits well within the broader frameworks of lean product development that have been evolving in both academia and industry. Two perspectives are discussed: the Womack and Jones framework and the Lean Enterprise Model.

1.3.1. The "Lean Thinking" Framework

From an industry perspective, the best known lean framework is the one presented by Womack and Jones (1996) in *Lean Thinking*. Their conception of lean has five primary aspects:

1. Understand value from the customer's perspective
2. Eliminate waste
3. Make the product flow
4. Control the flow using pull
5. Strive for perfection.

This framework can be enhanced by considering the different levels within and between organizations at which lean concepts might be applied. Figure 1.1 illustrates these levels in the shape of a pyramid. At the base are the individual people who make up an organization. People are then brought together on teams, and teams work together on a specific project (or program). Above projects are a company's divisions and then its corporate executive organizations. Multiple organizations then come together at the top of the pyramid to form the extended enterprise.

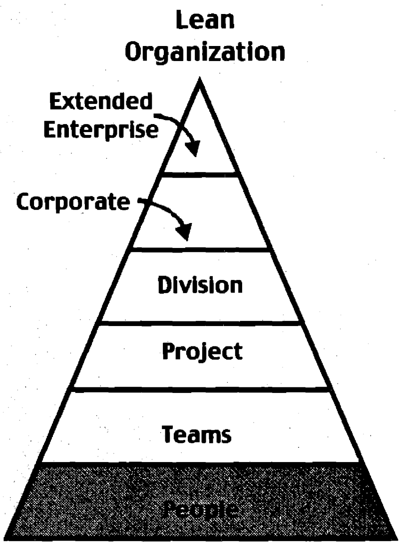

Figure 1.1: The different levels of the extended enterprise.

The goals of this research can be understood by combining this perspective of the extended enterprise with Womack and Jones' framework, as shown in Figure 1.2. First, this study aimed to understand how individuals on product development teams defined value and how such definitions can vary. With an understanding of value, waste in communication can then be identified and efforts directed at reducing it. The heart of this research fits across the notions of flow and pull: this investigation identified tools, techniques, and methods for improving communication on design teams, or, put another way, for facilitating the flow and pull of product development information. Finally, the models of communication developed through this study represent a new model of perfection for product development information sharing.

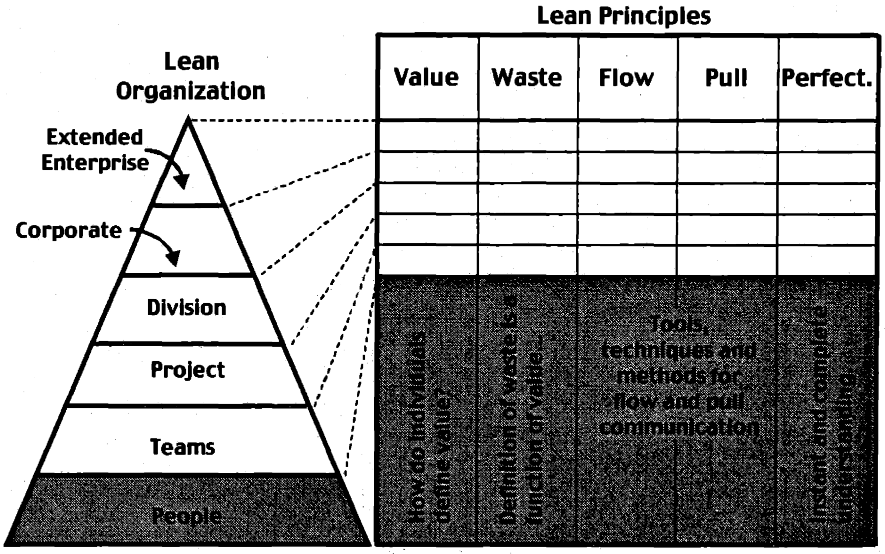

Figure 1.2: The goals of this study relative to Womack and Jones' principles, and the organizational level to which this study applies.

1.3.2. The Lean Enterprise Model

The Lean Enterprise Model (LEM) is a framework for lean that was developed by the Lean Aerospace Initiative at MIT. It provides a mechanism for both organizing research results as well for guiding lean implementation efforts. The LEM's core is formed by twelve Overarching Practices (OAPs). These practices are listed and defined in Table 1.1 below.

Table 1.1: The LEM's overarching practices (adapted from LAI, 2000).

Overarching Practice	***Definition***
Identify and Optimize Enterprise Flow	Optimize the flow of products and services, either affecting or within the process, from concept design through point of use.
Assure Seamless Information Flow	Provide processes for seamless and timely transfer of and access to present information
Optimize Capability and Utilization of People	Assure properly trained people are available when needed
Make Decisions at Lowest Possible Level	Design the organizational structure and management systems to accelerate and enhance decision making at the point of knowledge, application, and need.
Implement Integrated Product and Process Development (IPPD)	Create products through an integrated team effort of people and organizations which are knowledgeable of and responsible for all phases of the product's life cycle from concept definition through development, production, deployment, operations, and support.
Relationships Based on Mutual Trust and Commitment	Establish stable and on-going cooperative relationships within the extended enterprise, encompassing both customers and suppliers.
Continuous Focus on the Customer	Proactively understand and respond to the needs of the internal and external customers.
Promote Lean Leadership at All Levels	Align and involve all stakeholders to achieve the enterprise's lean vision.
Maintain Challenges of Existing Processes	Ensure a culture and systems that use quantitative measurement and analysis to continuously improve processes.
Nurture a Learning Environment	Provide for the development and growth of both organizations' and individuals' support of attaining lean enterprise goals.
Ensure Process Capability and Maturation	Establish and maintain processes capable of consistently designing and producing key characteristics of the product or service.
Maximize Stability in a Changing Environment	Establish strategies to maintain program stability in a changing, customer-driven environment.

Given this investigation's focus, its results address the following OAPs:

- *Assure Seamless Information Flow.* The results from this study contribute to product developers' understanding of why communication can be difficult, thereby improving their abilities to overcome such challenges and facilitating improved information flow throughout an organization.
- *Make Decisions at the Lowest Possible Level.* As will be discussed, this study found that problem solving performance was highest when teams were able to solve problems on their own without management intervention. The results of this investigation, therefore, provide guidance as to how to facilitate such low-level decision making.
- *Implement Integrated Product and Process Development (IPPD).* By its very nature, IPPD requires individuals from different technical specialties to work together. The focus of this study was on enhancing such skills by improving communication practices on IPPD teams.

- *Relationships Based on Mutual Trust and Commitment.* The techniques and methods discussed in this study provide practical approaches for product developers to build such relationships while working on multidisciplinary teams.
- *Nurture a Learning Environment.* An important component of learning on product development teams is enhancing team members' appreciation of what is important to other members on the team. The results of this study provide guidance on how to facilitate such learning.

1.4. Dissertation Overview

This dissertation is organized essentially according to how the project itself evolved. The next two chapters develop the theoretical foundations for this work. Chapter 2 provides an understanding of the underlying concept of this project: integration. It begins by first developing a definition for a system, and then using that definition to clarify the meaning of the term "integration". Building on the product development management literature, the chapter goes on to argue that integration is a social process. The origins of differentiation within organizations are explored, as is the resulting need for integration.

Chapter 3 then reviews the dominant model of organizational communication, the information processing framework, and suggests why this model is not adequate for addressing the problems studied in this investigation. A new communications model is then developed, based primarily on the theory of abstraction. This revised model better captures the need for two individuals to actively create a shared system of meaning during their communication exchanges, and, therefore, provides a better understanding of the social challenges of integration as well as suggesting methods for overcoming these challenges.

Chapter 4 describes the experimental methods used to study problem solving practices on multidisciplinary design teams. First, it reviews integration tools and techniques that have been identified by other researchers. Given these past findings, the specific issues to be investigated during this project are presented, along with the methods used to acquire data related to these issues. Three hypotheses are developed, along with the measures that are used to support or refute them.

Chapter 5 reviews the key findings of this project. It first discusses factors identified during this study that facilitate or hinder the problem solving process. Then, the data's implications for each of the three hypotheses are discussed in turn. Several additional observations, pertaining to issues not originally intended to be studied during this project, are then reviewed.

Chapter 6 provides recommendations to both product development practitioners and researchers. Based on the conclusions from this study, a variety of practical suggestions are presented that could be used to improve communication, and integration, on product development teams. Additionally, several recommendations are made to researchers, both regarding improvements to communication models as well as potential avenues for future research. The dissertation then concludes by returning to where it had begun, arguing that integration, and hence, product development performance, is a function of communication.

Finally, appendices provide supplementary information, primarily details of data analyses. Also included as an appendix is a brief tutorial describing how to implement improved versions of the data collection methods used for this study.

2. SYSTEMS AND SYSTEMS INTEGRATION: TOWARDS A SOCIAL PERSPECTIVE

The following two chapters will establish the theoretical foundations for this research, which are based on two major streams of literature: systems integration and theories of communication and knowledge. This chapter will address the topic of integration. While the challenges of integration are often discussed in engineering circles, these discussions tend to focus solely on technical issues, disregarding the human dynamics that occur on design teams. Prior to delving into such a social perspective, a more technical-oriented view of integration will first be presented.

2.1. Systems Integration

"Integration" is a term that often takes on a new meaning with each piece of literature written about it, and this wide range of definitions complicates and confuses discussions about the concept. Such confusion is especially troublesome, because, as will be discussed below, how well a product's elements are "integrated" can be a significant indicator of a product's success in the market place. Furthermore, since integration is a central theme to this work, it is worthwhile to develop a specific and clear definition for the term. In order to define integration, however, the concept of a system must first be explored.

2.1.1. Definition of a System

Many authors have attempted to provide definitive definitions of a "system." Following is a brief list of some of these attempts (listed chronologically by date of publication):

> Morton (1971): A system is "an integrated assembly of specialized parts acting together for a common purpose" (p. 12).
>
> Blanchard and Fabrycky (1981): "A system is a set of interrelated components working together toward some common objective" (p. 4).
>
> Grady (1994): Systems are "combinations of parts that together perform some function that no subset of the parts could achieve" (p.16).
>
> Martin (1997): A system is "a set of integrated end products and their enabling products" (p. 17).
>
> IEEE Std 1220-1998: A system is "[a] set or arrangement of elements (people, products [hardware and software] and processes [facilities, equipment, material and procedures]) that are related and whose behavior satisfies customer/operational needs, and provides for the life cycle sustainment of the products" (p. 8).
>
> Sage and Lynch (1998): A system is "a connected structured set of elements that perform functions that serve some intended purpose" (p. 177).

Two pervasive themes emerge from these definitions. First, a system consists of multiple parts connected in some fashion. Second, when connected, these parts are acting to achieve a common goal that they could not achieve on their own.

All of these themes are perhaps best captured by Ackoff (1974), who defines a system as "a set of two or more interrelated elements of any kind," that satisfies the following three conditions:

> 1. The properties or behavior of each element of the set has an effect on the properties or behavior of the set taken as a whole.
>
> 2. The properties and behavior of each element, and the way they affect the whole, depend on the properties and behavior of at least one other element in the set. Therefore, no part has an independent effect on the whole and each is affected by at least one other part.
>
> 3. Every possible subgroup of elements in the set has the first two properties: each has a nonindependent effect on the whole. Therefore, the whole cannot be decomposed into independent subsets. A system cannot be subdivided into independent subsystems. (p. 13)

A system, therefore, is characterized primarily by the fact that is composed of multiple elements, and the system's performance depends on the *interaction* between those elements and the environment in which they function.

As an example of this definition of a system, consider the human body[1]. Every organ in the body affects the body's (the system's) performance (property 1). Furthermore, the heart's behavior and performance, an element of the body, is affected by the behavior and performance of the lungs, another element (property 2). Finally, removing a heart from the body effectively destroys the performance of the entire body (property 3). Thus, the human body, since it satisfies all three conditions, can be considered a system.

A system can also be defined in terms of its *structure*, *function*, or *purpose* (Rechtin and Maier, 1997; Sage and Lynch, 1998). Ackoff's definition focuses primarily on the structural perspective – that a system is composed of individual elements and depends on the interaction of those elements for its operation. Similarly, Simon (1969) defines a hierarchic system as "a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure..." (p. 87). A functional definition of a system, in contrast, focuses on what a system does, while a purposeful definition focuses on its goals. Thus, a structural definition of a desk chair might describe how the wheels are connected to the base, the base to the frame, the frame to the cushion, etc.; a functional definition might describe how a person moves from a standing to a seated position using the chair; and a purposeful definition might state that the goal of the chair is provide a comfortable place to sit while working at a desk. All of these definitions are important, and, in fact, illustrate why a system and its meaning can become so complicated: Not only are all of different definitions of a chair correct, they are all needed to fully define the chair.

Modifying Ackoff's definition slightly, the following definition of a system will be used for the remainder of this work:

> *A system is defined as a set of two or more interrelated elements of any kind working together for a common purpose that satisfies the following three conditions:*
>
> *1. The properties or behavior of each element of the set has an effect on the properties or behavior of the set taken as a whole.*
>
> *2. The properties and behavior of each element, and the way they affect the whole, depend on the properties and behavior of at least one other element in the set. Therefore, no part has an independent effect on the whole and each is affected by at least one other part.*
>
> *3. Every possible subgroup of elements in the set has the first two properties: each has a nonindependent effect on the whole. Therefore, the whole cannot be decomposed into independent subsets. A system cannot be subdivided into independent subsystems.*

2.1.2. Definition of Integration

As the above discussion suggests, a key element of a system is the manner in which its elements are connected, i.e., how the system is "integrated". Unfortunately, many definitions of integration are quite vague. While Ackoff's definition of a system provides for a testable standard (e.g., if and only if an object meets all three conditions can it be called a system), most definitions of integration are so general that they shed little light on the problem embodied in the concept. For example, Grady (1994) defines system integration as "the art and science of facilitating the marketplace of ideas that connects the many separate solutions into a system solution" (p. 3). Similarly, Sage and Lynch (1998) define integration as "efforts to ensure

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[1] This example is based on Ackoff (1974), p. 13.

appropriate communication between elements – including technology, human, and organizational – that are supposed to work together" (p. 176). While not especially clear, these definitions do illustrate a common theme in most writing about integration – integration is viewed as a *process*.

Rather than relying on such general descriptions of integration, however, the definition of a system can be used to generate a more refined definition of integration. As noted above, for something to qualify as a system, it must meet three requirements. In general, these requirements state that a system is able to do things that its components alone cannot do, and that the components each have an effect on each other. Therefore, integration can be defined as:

> *The process of combining a set of elements such that the combination exhibits properties not exhibited by any element independently.*

Note that this definition is testable: If a combination of components can function together to implement a function no single component can do on its own, the combination can be called "integrated." Also note that this definition does not specify any requirements for the "quality" of the integration. Therefore, several components might be "integrated," but might not be "well integrated." However, such qualitative descriptions are dependent upon the perspective of the individual judging the process, and, therefore, need not be part of the formal definition. Finally, as is true for the definition of a system, no restriction is placed on what the "elements" might be – an element might be a bolt, a tube, an engine, a person, a muscle, a musical instrument, etc.

2.1.3. The Importance of Integration

Although a precise definition of integration is difficult to find in the literature, examples of the process's importance are not. Two primary lines of research provide excellent evidence for the need to focus on integration: product development research illustrating the impacts of integration on product performance, and innovation management studies that demonstrate the importance of one particular type of integration process, architectural innovation.

Some of the most comprehensive research on integration has been conducted by Iansiti. His research has emphasized a particular type of integration activity, which he refers to as "technology integration:" "the set of investigation, evaluation, and refinement activities aimed at creating a match between technological options and application context" (Iansiti, 1998, p. 21). Thus, technology integration consists of those decisions that lead a company to combine several technologies to create a new product. Iansiti's research suggested that this skill, more than any other (such as project management, leadership, or organization) was the most important in determining the success of new product development effort (Iansiti and West, 1997). Essentially, early decisions about what technologies should be combined frame the problem to be addressed by the product development process. If the selected technologies can be combined easily, the product development effort as a whole is more likely progress smoothly. If, on the other hand, the technologies can not be readily combined, the development process will be difficult, no matter the skill level of the project's team.

A series of studies in the automotive industry, most notably those by Womack et al (1991) and Clark and Fujimoto (1991) also demonstrated the importance of integration. Both of these investigations revealed the significance of design for manufacture and assembly. Specifically, the researchers found that the more the product's design took into account the capabilities of the manufacturing system that would produce the product, the better the final product's quality. In addition, Womack et al (1991) demonstrated that the better integrated the product and its manufacturing system, the better the manufacturing system's performance. Again, the point is clear: the better integrated the system (in this case, the "system" being the product and its manufacturing facilities), the better the system's performance.

Similarly, a study of pharmaceutical development projects in the United States and Europe by Pisano and Wheelwright (1995) also demonstrated the importance of integrating product and process design. In this study, the authors attributed the root cause of many delayed product launches or products suffering from limited success to "senior managers' belief that process [manufacturing] technology was not very important" (Pisano and Wheelwright, 1995, p. 94). Essentially, managers tended to focus their attention on designing the product, rather than on designing the manufacturing system. However, many of the product's final performance parameters were controlled by the manufacturing process. Therefore, although the product's design may have matured, the manufacturing techniques used to the produce the product had not. This lack of maturity in manufacturing then led to delays and problems with the product, which in turn had a dramatic impact on the overall success of the development effort. As in the case of automobiles, the basic issue was a failure to effectively link the manufacturing processes and the product design to create an overall successful development effort.

These same problems exist in government programs as well. In a study comparing defense acquisition practices to product development practices in the commercial world, the United States General Accounting Office (1998) found that, in general, defense programs took longer and carried greater amounts of risk through their development than comparable commercial projects. Furthermore, much of the risk in DOD programs tended to lie between major program elements, such as product design and manufacturing system development. The GAO found that many DOD projects tended to ignore manufacturing concerns until just prior to the start of production. The result of this delayed consideration was that many programs experienced significant problems once production began and design flaws related manufacturability were finally revealed. Thus, as in the automotive and pharmaceutical industry studies, the failure to *integrate* the product and manufacturing systems designs led to significant downstream development problems.

The United States Air Force Engineering Directorate (1998) came to a similar series of conclusions about the problems it was observing during its development programs, especially at the transition point from product design to production. In particular, the Directorate noted that a key factor in many of the delays and manufacturing quality problems stemmed from a failure to understand "the linkage between key design requirements, the [manufacturing] processes needed to support them, and the impact on product performance, supportability, and cost." While specific technologies or manufacturing processes may have been developed to a significant degree independently, the interactions between these elements had not been considered – the programs had failed to consider integration issues.

Another view of the importance of integration can be gained by considering the concept of architectural innovation. Henderson and Clark (1990) provide a good foundation of definitions for architectural innovation. First, they define a "component" as "a physically distinct portion of the product that embodies a core design concept… and performs a well-defined function" (p. 11). Thus, a component is analogous to Ackoff's "element". Next, a product's "architecture" refers to how the components of the product are connected and combined. Therefore, "architectural innovations" are "innovations that change the way in which the components of a product are linked together, while leaving the core design concepts... untouched" (Henderson and Clark, 1990, p. 10). Essentially, architectural innovation changes the way a product's components (a system's elements) are linked (are integrated) without changing the components themselves.

The market significance of architectural innovation is not trivial. As Abernathy and Clark (1985) note, architectural innovation tends to open up new markets and entirely new industries. These conclusions have been supported by Clayton Christensen, who has done some of the most comprehensive research in this field. In his studies of the computer hard drive industry, Christensen has developed the notion of "disruptive technologies," a special case of architectural innovation (Bower and Christensen, 1995; Christensen 1992b; Christensen, 1997). Like an architectural innovation, a disruptive technology is a product that combines existing components in a new fashion. Typically, a disruptive technology has lower performance along traditional performance measures than does a more conventional product. However, disruptive technologies are characterized by enhanced performance relative to a new measure of performance along with rapid improvement in performance relative to old measures. Thus, a disruptive technology offers new features and capabilities to its customers.

Christensen found that when a disruptive technology entered a market, it eventually replaced the traditional product. Furthermore, the disruptive technology was often developed by a new entrant firm, that, with the rise of the new product, often replaced the old market leaders as the dominant player in the industry. As this research indicates, the fashion in which a product's components were combined -- the fashion in which they were integrated -- affected not just the performance of a given product and its development effort, but the entire marketplace of which that product was a part.

2.2. Differentiation and Integration in Organizations : A Social Perspective of the Integration Process

The above studies all demonstrated the importance of integration as a critical factor in the success of product development efforts. However, all of the investigations described above tended to focus on the integration of the *technologies* involved in the design of a new product, such as the product components or the product and its manufacturing system. The process of integration, however is not simply a technical one, but a social one as well. During a product development effort the different technologies that must be integrated are often represented by different people. Integrating those technologies then becomes a function of the social relationships between those individuals and their ability to effectively share and exchange the knowledge and expertise they have related to the development of the product. Thus, integration problems can be viewed as social problems. Consequently, improving a firm's ability to integrate the various technologies in its products requires improving the communication skills within a firm. Understanding this social perspective of integration first requires an understanding how the different technologies needed for a new product come to be represented by different groups within and organization, a concept referred to as "differentiation".

2.2.1. The Need for Differentiation and Integration

Like any other type of system, an organization is created to enable its elements (people) to achieve goals they could not achieve alone. In addition, like any other system, the people within an organization are not homogeneous, and may, in fact, be quite heterogeneous. This heterogeneity can arise from a variety of factors.

Perhaps the first cause of heterogeneity, or "differentiation" (Lawrence and Lorsch, 1967), relates to the need for an organization to take in and process a wide variety of information from its environment. This environment is likely filled with complexity, uncertainty, and equivocality (Weick, 1976). In order to process all of the various signals it may take in, an organization must create an information receiving network whose complexity matches that of the environment. This notion, of matching the complexity of the receiver to the complexity of the signal, is known as requisite variety (Morgan and Ramirez, 1983; Van de Ven, 1986; Weick, 1976). Thus, as the uncertainty in an organization's environment increases, the members of the organization tend to take on more and more specialized roles (Griffin and Hauser, 1996; Utterback, 1982). Such specialization allows an organization to take large, complex, unmanageable problems and divide them into smaller ones that can be addressed and solved more readily (Adams, 1998; Grady, 1994; Krishnan, 1997; Simon and March, 1966).

Although they did not refer to the concept as requisite variety, Lawrence and Lorsch (1967) did one of the most definitive studies of its importance. In their investigations, the researchers found that high performing organizations tended to more closely match their complexity to that of the environments which they faced. Thus, high performing organizations in dynamic or complex markets tended to be highly differentiated -- composed of a large number of specialized subgroups -- which, together, were able to execute all of the diverse functions needed to operate effectively in their environment. Similarly, high performing organizations in less fluid environments tended to lack this differentiation and had a more homogeneous make-up. Lower performing organizations failed to recognize these distinctions or to organize appropriately for them. Therefore, the researchers concluded that the ability to effectively differentiate was a significant factor in predicting organizational performance.

Differentiation is also driven by the increasing knowledge base that is created by each successive generation of human innovation (Morton, 1971). As Norman (1993) observes:

> Each new advance of technology added to the powers and abilities of human society; each new advance also added to the amount of knowledge that newer generations would have to learn… The background knowledge required more and more learning, thereby leading to specialization. (p. 8)

Thus, as technologies become more advanced and complex, an individual's ability to master multiple disciplines is reduced. Consequently, an organization requires more people with more specialized skills so that in total it has all of the knowledge required to meet its ends.

The needs for an organization to match the complexity of its environment or knowledge base are not the only factors driving it to differentiate, however. Another important reason for the heterogeneity of an organization's members relates to its ability to innovate. As many researchers have noted, diversity of talents tends to foster the development of new ideas. Leonard-Barton (1995), for example, refers to "creative abrasion," the productive conflict that can occur between different groups that helps to dislodge old concepts and create new ones. Nonaka and Takeuchi (1995) make a similar observation based on their studies of new product development projects, noting that "… it is precisely such a conflict that pushes individuals to question existing premises and to make sense of their experiences in a new way" (p. 239). Lawrence and Lorsch (1967) and Senge (1990) also stress the importance of conflict and diversity of opinion, although they both note that conflict can also become "dysfunctional" (Senge, 1990). This need for heterogeneity is recognized in many firms, and Honda and Toyota, for example, specifically seek to create teams that include people with a range of backgrounds and expertise (Nelson et al, 1998; Sobek et al, 1998).

Finally, differentiation may also be driven by such "mundane" factors as people's interests. As both Lawrence and Lorsch (1967) and Leonard-Barton (1995) observe, individual people are different and, consequently, they have varied interests and skills. These individual differences create diversity in any organization, no matter how simple or complex its environment. Furthermore, an organization must often define its skill sets and disciplines based on “the structures of trades and professions in the broader social environment” (Simon and March, 1966). Thus, the diversity of skills in an organization is also driven by the society in which the organization is situated, as well as the specific interests and talents of its members.

Given the potential for differentiation within an organization, its ability to integrate, or “reintegrate” (Piore et al, 1994), the skills and knowledge of its members is of extreme importance. Thus Van de Ven (1986) observes, “[p]erhaps the most significant structural problem in managing complex organizations… is the management of part-whole relationships” (p. 598). In the Lawrence and Lorsch study cited above, in fact, the high performing organizations not only more successfully matched the complexity of their environments, they also better integrated their diverse specialty groups than did the low performing organizations. Similarly, in a review of management of innovation literature, Pavitt (1990) identified the capacity to integrate knowledge from multiple disciplines as an important success indicator. In addition, Kogut and Zander (1992) found that a firm’s “combinative capabilities,” a firm’s ability to combine old knowledge in new ways or with new ideas, was a key factor in successful innovations. Weick (1976) notes that a primary purpose of organizing, in fact, is to facilitate a method of exchanging ideas between different individuals or groups, a conception supported by Nonaka and Takeuchi (1995) as well. Iansiti and Clark (1994) also warn that an underlying need in many organizations is the ability to merge, or integrate, the different streams of knowledge within a firm. And Sethi (2000), in a survey of marketing managers leading new product development teams, found that “information integration” was positively related to new product quality. Thus the central question for the remainder of this work is, how can the different knowledge bases of an organization's individuals or subgroups be combined such that the organizational as a whole can achieve more than any of the individuals or subgroups can achieve alone?

2.2.2. The Consequences of Differentiation

While the previous section identified many reasons for and benefits of differentiation within an organization, there are also significant drawbacks. The integration process is fraught with difficulties, and conflict between subgroups is a frequent occurrence in many organizations. Fundamentally, these problems can be traced to the identities that individuals create for themselves based on their designated or selected specialty disciplines. As Lawrence and Lorsch (1967) explain:

> When people live day in and day out in a specialized role, they tend to see their own organizational surroundings in terms of that role. The more personally involved in their jobs they become, the more this is true. Such involvement often leads them to personalize the conflicts that arise with representatives of other organizational units. Of course they know logically that an organization needs different kinds of specialists, but they forget the full meaning of this when they run into a particular person who is 'impossible to work with.' Then they all too readily turn to an explanation based on personality traits that writes off the individual as an oddball and justifies their own withdrawal from or forcing of the conflict. (p. 216)

Similarly, Leonard-Barton (1995) describes "signature skills," which are skills or abilities by which a person tends to identify him- or herself. The development and cultivation of these skills tends to become "emotionally tied to people's egos and identities" (Leonard-Barton, 1995), and, consequently, any changes that might threaten these skills is viewed as "bad".

For example, Morison's (1966) study of naval gun improvement efforts found that individuals' resistance to change was tightly linked to their narrow definitions of their own roles and responsibilities. Although a new aiming innovation significantly improved the accuracy of naval guns, many officers staunchly refused to implement the new technology. Their resistance originated from their perception that the new aiming system threatened to replace the manual skills they had originally cultivated when they joined the navy. Therefore, the technology threatened their own self-identities, and, to preserve their sense of purpose and status in the navy, these experienced officers tried to block the acceptance of the new aiming system. This personalization of technical decisions often results in disagreements between specialty groups rapidly acquiring "the aspect of ideological disputes" (Burns and Stalker, 1961,p. 11).

These disputes are perpetuated within an organization because each of the subgroups will evolve to have its own ends and goals (Allen, 1988; Burns and Stalker, 1961; Carlile, 1997; Dougherty, 1992). Thus, a product development organization's design group will place utmost priority on a product's performance, while manufacturing will worry almost exclusively about its ability to meet its production quotas, and marketing will be concerned with meeting sales goals (Carlile, 1997; Dougherty, 1992). These different goals will color how individuals from each group view the world and how problems should be prioritized and addressed. As Simon and March (1966) note, when these different views are combined with mutual dependence (e.g., manufacturing is dependent on design to create products for it to produce and design is dependent on manufacturing to manufacture its designs) conflict is a likely outcome.

Resolving these conflicts becomes all the more difficult because the division of labor that may exist between an organization's subgroups is arbitrary. As Piore et al (1994) explain, differentiation is often based on four false assumptions: (1) that there is a unique way to divide a problem, (2) that the partitioning of a given problem is based on nature, (3) that the cost of division is equal to the cost of integration, and (4) that integration is straightforward. The consequence of decisions based on these incorrect assumptions is that knowledge and skills that should reside within one part of an organization are split between several areas (Boland and

Tenkasi, 1995; Krishnan et al, 1997). As a classic example, Bohn (1994) and Klein (1994) both note that the application of Taylorism to factories resulted in the splitting of the knowledge needed to understand *why* a factory is arranged the way it is (knowledge that became resident with engineers) and the knowledge needed to actually *operate* the factory (which resided with the factory workers themselves). In reality, however, these two knowledge bases interact, and a complete understanding of a factory's performance requires both. In this case, the process of differentiation led to the false impression that two separate bodies of knowledge existed in nature, when in fact the division was created by humans.

Another consequence of differentiation, and the organizational divisions it creates, is that it can inhibit the ability of a firm to think in new ways (Adams, 1998; Henderson and Clark, 1990; Piore et al, 1994). To some extent, what a firm "knows" is embedded in how it is organized (Dougherty, 1992; Fiol, 1994; Klein, 1994; Kogut and Zander, 1992). As described above, for example, knowledge of how to operate a factory lies with one group, while knowledge about how to design the factory resides with another. These divisions can lead to "islands of knowledge" (Leonard-Barton, 1995) across which the flow of ideas is inhibited.

Furthermore, organizations tend to departmentalize themselves as if the world were static (Simon and March, 1966). The world, however, is actually dynamic, and, as a consequence of this mismatch, organizations can be slow to adapt to changes in their environments. In fact, in studies by Imai et al (1985) and Nonaka and Takeuchi (1995), researchers found that successful firms were often characterized by a willingness to forget what they had learned in the past and to abandon practices that had been successful on previous projects. As noted above, organizational structures tend to create rigidity to a firm's practices (Weick, 1976; Senge, 1990), however, inhibiting its ability to make such changes.

As this discussion has highlighted, differentiation is critical to a firm's ability to succeed in the marketplace, but unless sufficient attention is paid to integration processes, differentiation can also be a significant contributor to a firm's failure. It is worthwhile, therefore, to consider inter-group communication processes in greater detail in order to better understand how an organization's subgroups may be integrated.

3. THEORIES OF COMMUNICATION AND KNOWLEDGE

As discussed in the previous chapter, a firm's success in developing new products hinges on its ability to first differentiate itself such that its complexity matches that of its environment and to then recombine the skills and talents of the differentiated units to deliver a final, integrated product. Therefore, the effectiveness of the communication processes between specialized subgroups of an organization represents a critical element in delivering successful products or services.

This chapter will consider the communications problem in detail. First, the current dominant model of communication, the information processing framework, will be reviewed, as will its shortcomings. Then an alternative theory will be developed, which will be used as the primary theoretical framework for the remainder of this work.

3.1. The Information Processing Framework

The information processing framework for communication within an organization is based on the theories of communication first developed by Shannon and Weaver during the late 1940s. (Shannon and Weaver, 1963). This framework has helped to facilitate many improvements in inter- and intra-organizational communication practices, but, as will be described, this theory does not account for some significant and problematic features of human communication.

3.1.1. Overview of the Information Processing Framework

The major components of the information processing framework are illustrated in Figure 3.1. An *information source* pulls information from its environment and composes a message that is to be sent. The *transmitter* is the device used to send the message, in the form of a *signal.* During transmission, *noise* may be inserted into the signal by a *noise source,* potentially damaging elements of the signal. A *receiver* acquires the *received signal,* consisting of the original signal plus any noise that may have been inserted into it. The receiver decodes the signal into the *message,* which then arrives at its intended destination.

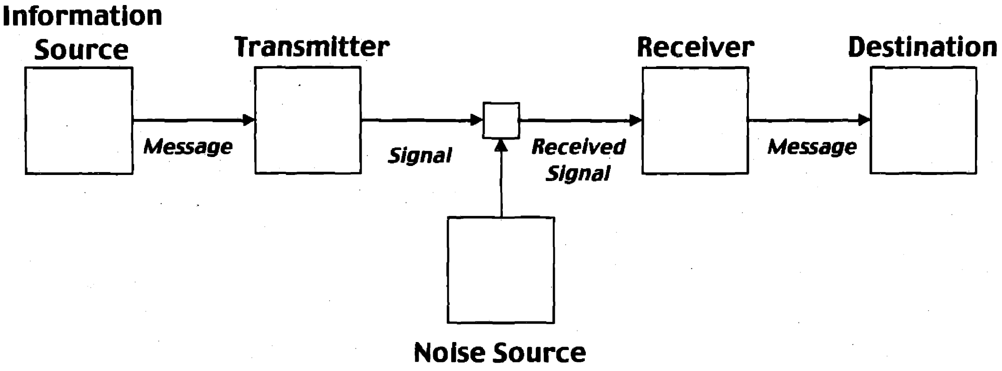


Figure 3.1: Shannon and Weaver's model of a communication system (adapted from Shannon and Weaver, 1967).

Figure 3.2 applies this model to two people talking to each other. In this case, both the information source and the destination are people. The first person to speak, the source, composes a message based on his observations of the environment. The message is then transmitted by the person's voice, the signal taking the form of sound waves of spoken words. Noise may be introduced into the signal, such as background sounds in the room, a person's accent, etc. The received signal is then heard by the destination person's ears. She then decodes the signal, receiving the original message.

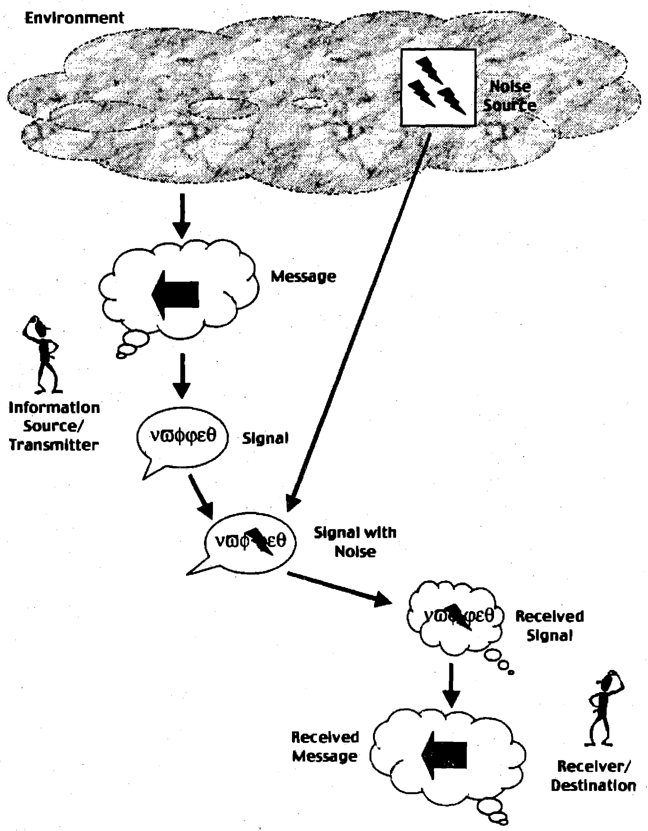


Figure 3.2: A depiction of human communication based on Shannon and Weaver's model.

This illustration highlights some of the key assumptions of the information processing model. First, and perhaps most important, both the source and the destination share a common understanding of how to translate between signals and messages, e.g., they both share the same definitions for the words they speak and hear. Furthermore, because of this shared understanding, the receiver is able to filter out any noise that is inserted into the signal, a second important assumption. Finally, this model assumes that both actors are rational, i.e., the model assumes the actors will act dispassionately, and emotions will not color their interpretation of a message or their choice of what message is sent.

This framework has been the dominate model of organization communication for more than fifty years (Carlile, 1997; Nonaka and Takeuchi, 1995). For example, Burns and Stalker (1961) viewed an organization as an "interpretive system," which receives information from the environment, carries out operations on that information, and then retransmits it. Similarly, Simon (1969) conceived of learning within an organization as closely resembling Shannon and Weaver's information processing model. Galbraith (1973) also used the information processing analogy, describing organizations as "information-processing networks." And Clark and Fujimoto (1991), in their comprehensive study of product development practices in the world automotive industry, used an "information perspective," stating that "product development is a process by which an organization transforms data on market opportunities and technical problems into information assets for commercial production" (p. 20).

Given this view of the human mind and communications as resembling the operation of a computer (Suchman, 1990; Walsh, 1995), many authors have focused on defining different "types" of knowledge. The goal of categorizing knowledge in this fashion is to facilitate the creation of the clearly understood definitions that help facilitate the communication process, improving cross-discipline integration and organizational performance. Table 3.1 lists some of the many "types" of knowledge identified in the literature, along with descriptions of each.

Table 3.1: "Types" of knowledge.

Nelson (1959)
  - *Facts or data: That which is observed in reproducible experiments*
  - *Theories: Man-made concepts that create relationships between facts*

Henderson and Clark (1990)
  - *Component knowledge: Knowledge pertaining to the design and operation of a product's components*
  - *Architectural knowledge: Knowledge about how to combine components to create a final product*

Kogut and Zander (1992)
  - *Information: Knowledge that can be readily transferred (e.g., facts and symbols)*
  - *Know-how: Knowledge about how to do something*

Bohn (1994)
  - *Data: That which comes directly from sensors*
  - *Information: Organized data; data with meaning*
  - *Knowledge: Understanding that allows for causal predictions and prescriptive decisions*

Klein (1994)
  - *Operational knowledge: Knowledge about how best to perform a task (acquired with practice)*
  - *Analytical knowledge: An understanding of the scientific principles underlying a task (acquired with teaching)*

Nonaka and Takeuchi (1995)
  - *Tacit knowledge: Knowledge that is difficult to codify or share with others*
  - *Explicit knowledge: Knowledge that is easily codified and shared with others*

Iansiti (1998)
  - *Domain knowledge: Knowledge that is self-contained and independent of any particular application*
  - *System knowledge: Context-specific knowledge about how to integrate elements of a system*

Ahmed, et al (1999)
  - *Data: Information that comes from sensors*
  - *Information: Awareness of the context of data*
  - *Knowledge: Interpretation of information*

3.1.2. Weaknesses in the Information Processing Model

While the information processing model has helped to improve communication effectiveness in many organizations, it is not without its weaknesses. Its primary deficiency lies in its assumption of stable, shared definitions of meaning between sources and destinations. As early as 1956, Boulding (1956) noted that Shannon's information theory "is not adequate, of course, to deal with problems involving the semantic level of communication" (p. 201). Furthermore, Morton (1971) refuted the computer-based analogy often used for organizations, noting that "though [they] are systems, *[organizations] are not machines!*" (p. 93).

While a computer program has well-defined categories of meaning established from the beginning, human communication is far more dynamic. Human-to-human communication "is not just a problem of processing, but of representing, creating, negotiating, and recreating knowledge" (Carlile, 1997, p. 11). The meaning of a signal must be constructed actively, during the course of the communication process. Therefore, the filtering of errors and the interpretation of messages does not occur in human relations as cleanly as it does in machine communications (see Figure 3.3), and the information processing model's assumption of shared meanings can not be applied to humans (Boland and Tenkasi, 1995).

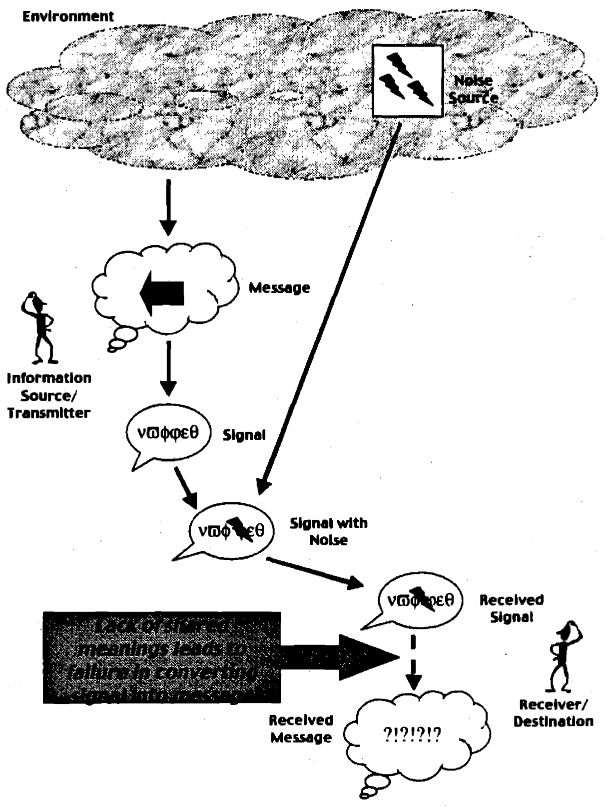


Figure 3.3: Flaws in the information-processing model. The lack of shared categories of meaning leads to failures in interpreting messages.

Given this lack of shared definitions of meaning, different subgroups within an organization will seem to speak different "languages" (Allen, 1988; Burns and Stalker, 1961; Cohen and Levinthal, 1990; Kogut and Zander, 1992; March and Simon, 1966; Morton, 1971; Schein, 1992). Thus, as Allen (1988) notes, these different languages create "an inherent problem whenever communications must take place across an organizational boundary" (p. 139). Furthermore, as groups become more specialized in their knowledge and skills, the "information receptors" of the groups also become more specialized. Consequently, a message that is clear to one group will be unintelligible to another, a condition Boulding (1956) refers to as "specialized deafness".

3.2. An Alternative Theory of Knowledge and Communication: The Process of Abstraction

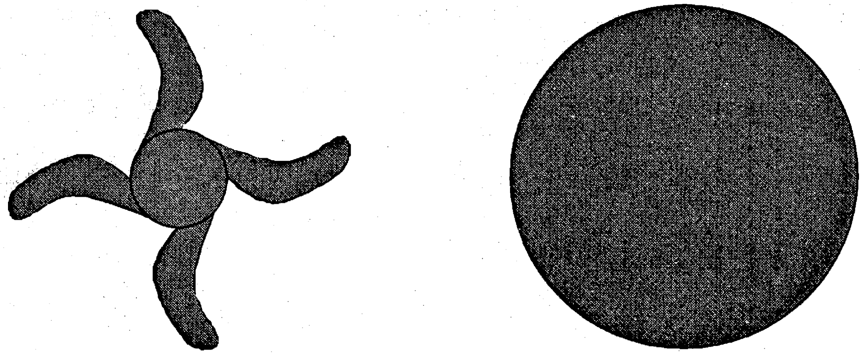
Overcoming the problems associated with the information processing framework require the development of an alternative model of communication that accounts for the initial lack of shared meanings. The theories of General Semantics, pioneered by Alfred Korzybski, provide a foundation for such an alternative theory. Originally developed in the 1930s and explained in great detail in *Science and Sanity*, Korzybski's ideas gave rise to expressions such as "the map is not the territory" and the habit of waving fingers in the air to put "quotes" around words that are used in specialized or questionable ways (Pula, 1994).

The following sections will develop an alternative communications framework to the information processing model based on General Semantics. First, several fundamental concepts will be reviewed, providing a basis for an explanation of Korzybski's theory of abstracting. Details of his theories will then be discussed, supplemented by more recent work in related fields. At the conclusion of this chapter, an alternative model of communication will have been developed, one that more fully captures the challenges of human relations than does the information processing model.

3.2.1. Foundations for General Semantics: Processes, Order, and Relations

In order to understand some of the basic concepts of human perception and communication as formulated in General Semantics, it is necessary to first describe some of the theory's underlying premises about the nature of the world. First, and perhaps, most importantly, is the notion of a "process" view of the world. Rather than considering the world as static, or unchanging, General Semantics starts from the premise that the world and everything in it – inorganic and organic objects – are "composed of some dynamic, fine-grained processes" (Korzybski, 1994, p. 383). Thus, when referring to a substance such as "iron" one is actually referring to a "persistence for a limited 'time' of certain gross characteristics, representing a process" (Korzybski, 1994, p. 162).

The appearance of stability or constancy of an object, Korzybski argues, is actually a result of humans' limited perceptive capabilities, and he uses the analogy of a spinning fan to illustrate the point (see Figure 3.4). A fan consists of a finite number of blades. However, when spinning at high speed, the blades blur, and give the appearance of a solid disk. Similarly with other objects encountered by humans – while objects may the appearance of permanence (like the "solid" fan disk), they are in fact changing continuously. Therefore, no object, not even a person, is ever exactly the same at any given instant.



A stopped fan... All of the individual blades are visible.

A spinning fan... The blades blur into a "solid" disk.

Figure 3.4: Korzybski's analogy between a spinning fan and human perception of processes (adapted from Korzybski, 1994, p. 383).

This dynamic, process-oriented view of the world then leads Korzybski to focus on *order*. That is, if things change, they change from some initial state to a new state, and then another, and another, etc. He notes that though it must remain as an undefined term, "order" conveys a "sense of betweenness... If we say that *a*, *b*, and *c* are in the order *a*, *b*, *c*, we mean that *b* is *between a* and *c*, and we say, further, that *a*, *b*, *c*, has a different order from *c* , *b*, *a*, or *b*, *a*, *c*, [etc.]" (Korzybski, 1994, p. 152). Thus, the consequences of a given sequence of changes are specific and different than an alternative sequence of changes.

Finally, General Semantics assumes that no object can ever be in complete isolation. Therefore, an observation is always made *between* two objects, whether it be a human observing a falling apple or a tree falling in an empty forest. Given that objects always occur at least in pairs, it is always possible to conceive of some sort of *relationship* between them. So, Korzybski argues, the phrase "to be" actually means, "*to be related*" (Korzybski, 1994, p. 161).

3.2.2. The Process of Abstracting Part I: The Un-Speakable Level

Korzybski's most significant contribution to our understanding of the human mind was his development and formulation of the process of *abstracting*. Abstracting, he explains, can be thought of as "'selecting', 'picking out', 'separating', 'summarizing', 'deducting', 'removing', 'omitting', 'disengaging', 'taking away', 'stripping'" (Korzybski, 1994, p. 379). The human process of perception is a process of observing the environment, selecting some stimuli, combining others, and neglecting or ignoring others – it is a process of summarizing and integrating. Accordingly, "[w]hat we see is structurally only a specific *statistical mass-effect* of happenings on a much finer grained level. We *see* what we see because we *miss* all the finer details" (Korzybski, 1994, p. 376). Furthermore, a person abstracts *from* something, whether that something is the environment and events occurring around the person or one of the person's own thoughts.

Like any other process, the process of abstracting occurs in a specific *order*. Abstraction begins with a physical sensation, whether it be a touch, smell, sight, sound, taste, or an emotional feeling, and then progresses to ideas, inferences, and conclusions. Therefore, the lowest order abstractions occur at the "objective level," or the "un-speakable level", a term that expresses a concept that is often disregarded: "namely, that an object or a feeling… is *not* verbal, is *not* words… Thus, we can sit on an object called 'a chair', but we cannot sit on the noise we made or the name we applied to the object" (Korzybski, 1994, p. 34).

The un-speakable, objective level, or first order abstractions, include all physical objects as perceived by an individual (such as a chair) as well as emotional "feelings", and a person's physical actions and interactions with the environment. The distinction between this lowest order of abstraction and higher orders is significant. For example, one may "learn" how to drive a car based on verbal instruction from an experienced driver. However, even if the student can perfectly recite the instructor's directions, the student will not necessarily be a good driver – the *act of driving* is not the same as the *words* used to describe the act.

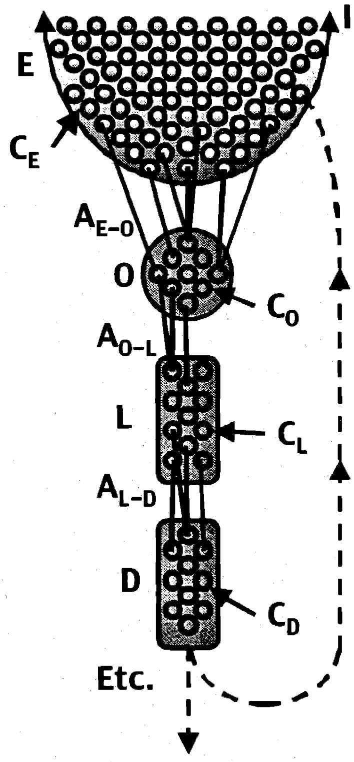
This distinction, between a verbal description of something and the act of doing it or the object itself, has more recently been reformulated as concepts of "tacit knowledge." Polyani (1966) first used this term, noting that "*we know more than we can tell*". That is, a student might "know" that he "knows" the material he has just studied, but he will find it difficult to express with words. Similarly, Nonaka and Takeuchi (1995) stressed the importance of tacit knowledge in the product development process. They described tacit knowledge as "knowledge of experience" or "of the body", and noted that it tended to be context-specific and hard to formalize or communicate. Carlile (1997), who also studied product development, described tacit knowledge as "embedded in know-how" and as "both difficult to access and transfer" (p. 18). Henderson (1991) also noted that tacit knowledge may not be verbalized because it cannot be. Korzybski's notion of the un-speakable level helps to clarify these observations: tacit knowledge is hard to communicate because is it is not *words*.

Consider, for instance, Nonaka and Takeuchi's example of the development of an automatic bread making machine (Nonaka and Takeuchi, 1995). The engineers developing the machine first interviewed expert bakers to learn how to make bread. They then went back to their lab and built a prototype machine. Though they had followed the exact instructions of the bakers, the bread produced by the machine was awful. After repeated efforts to fix the problems, the engineers finally sent one of their own to apprentice under the bakers. During the course of her apprenticeship, the apprentice baker/engineer learned that there was a particular twisting motion that the bakers used on the dough that was essential and that had been missed in the design of the machine. Nonaka and Takeuchi then call the knowledge of this twisting motion "tacit knowledge". Korzybski's term "un-speakable", however, seems more specific: the bakers could not convey this knowledge to the engineers during the interview simply because the motion was not words, and, therefore, could not be expressed verbally.

3.2.3. The Process of Abstracting Part II: Higher Order Abstractions

As noted above, the process of abstraction has a particular order, beginning with a person's sensations. More generally, the process of abstraction can be thought of as starting from a "scientific event" (Korzybski, 1994). Korzybski uses the term "scientific event" to refer to the infinite number of details, particulars, and aspects of any given event that occurs in nature. One can explore this notion using a classic riddle: If a tree falls in a forest with no one around, does the falling tree make a sound? Physically, the falling tree does disturb the air around it, producing sound waves – this is the "scientific event". The "sound" of a falling tree is a human being's abstraction of the sound waves entering her ear. Furthermore, the falling tree itself is not the only thing occurring in the forest – it just happens to be one aspect of the event. Hence the second level of abstraction: an "object", in this case the falling tree. The term, "falling tree" corresponds to the next level of abstraction, the label. Once a label has been applied to an object, higher order abstractions follow, such as descriptions ("the tree is brown", "it is falling fast", etc.), as well as inferences, conclusions, ("the tree must have been old"), etc.

In order to help explain the process of and orders of abstraction, Korzybski developed what he referred to as the "structural differential", illustrated in Figure 3.5. The structural differential helps to demonstrate several important points about abstracting. First, it highlights the basic orders, or levels, of abstraction: the *event* (E), from which is abstracted an *object* (O), from which is abstracted a *label* (L) from which is abstracted a *description* (D), etc., on to higher order abstractions. Each abstraction has associated with it some *characteristics*, or features, of that abstraction (C_E, C_o, C_L, C_D, etc.). Note that the event is illustrated with arrows at the top: these arrows indicate that there are an infinite number of characteristics associated with an event, not all of which can ever be completely captured. Furthermore, the structural differential clearly illustrates that each order of abstraction is separate from the others – the objective level, for example, is not the same as the verbal (label) level. Thus, Korzybski warns against the dangers of "confusing orders of abstraction".



Key

E	**An event**
I	**The arrows indicate that there are an infinite number of characteristics to the event.**
C_E	**A characteristic of the event.**
A_{E-O}	**The process of abstracting from the event to an object**
O	**An object abstracted from the event**
C_O	**A characteristic of the object**
A_{O-L}	**The process of abstracting from an object to a label**
L	**A label abstracted from the object**
C_L	**A characteristic of the label**
A_{L-D}	**The process of abstracting from a label to a description**
D	**A description abstracted from the label**
C_D	**A characteristic of the description**
Etc.	**The arrow at the bottom indicates the process can continue indefinitely, moving to inferences, conclusions, etc. The arcing line indicates that higher order abstractions can be used to explain characteristics of an event that are not directly observable.**

Figure 3.5: Korzybski's structural differential, used to highlight the major aspects of the process of abstracting (adapted from Korzybski, 1994).

Lines in the figure ($A_{E\text{-}O}$, $A_{O\text{-}L}$, $A_{L\text{-}D}$) represent the process of abstracting from one level to another. There are three important points about the abstracting process illustrated by these lines and the characteristics that they connect. First, not all of the characteristics of a lower level abstraction are carried over to the higher level – i.e., during the process of abstraction some details are left out or omitted. Hence, in the falling tree example, one may simply say that the tree is falling, without referring to the rate at which it is falling or the fact that that rate is changing. Second, multiple characteristics from one level may be represented by one characteristic at a higher level – abstraction is also a process of summary and integration. So, instead of referring to all of the branches and leaves of the tree and manner in which those branches and leaves are connected, one simply refers to a "tree". Finally, each level of abstraction has associated with it it's own, unique characteristics which do not exist on another level. For example, when the label "falling tree" is applied to the object, one can make statements about the label that do not apply to the tree itself, such as the label has two *L*'s and two *E*'s. The tree itself, however, does not have any letters associated with it.

This last point leads to the final features illustrated by the structural differential: the abstraction process can continue indefinitely and ultimately leads to a more thorough understanding of the event itself (Korzybski, 1994). That is, one can always say something more about an abstraction: the label "falling tree" has two L's; an "L" is drawn using one vertical line and one horizontal line intersecting at a right angle at their ends; lines may be drawn using a pen or pencil; etc. Furthermore, higher levels of abstractions allow humans to conceive of features of an event that may not be directly observable. Thus, physicists were able to predict the existence of black holes before a black hole was ever actually observed. The concept "black hole" represented an abstraction of physical processes that were suggested by other abstractions, or theories, about space-time and physics. More recently, Norman (1993) referred to abstractions of abstractions as "metarepresentations", and noted their significance stating that,

> [the] ability to represent the representation of thoughts and concepts is the essence of reflection and higher order thought. It is through metarepresentations that we generate new knowledge, finding consistencies and patterns in the representations that could not readily be noticed in the world. (p. 81)

Finally, Korzybski noted that there is no need to establish an "absolute" order to abstractions. Instead, it is important to simply recognize that there are multiple levels of abstractions and to be able to distinguish lower order abstractions from higher level ones. As will be discussed below, confusing orders of abstraction is common cause of many problems in organizations.

Since Korzybski introduced his theories about orders of abstractions, other authors have developed similar concepts. For example, Boulding's (1956) conception of a mental "image" is very similar to Korzybski's abstractions. Boulding observed that

> ... behavior is response not to a specific stimulus but to an 'image' or knowledge structure or view of the environment as a whole. This image is of course determined by information received into the organism; the relation between the receipt of information and the building up of an image however is exceedingly complex. It is not a simple piling up or accumulation of information received, although this frequently happens, but a structuring of information into something different from the information itself. (p. 204)

Likewise, Simon and March (1966) suggested that people use simplified "models" to understand the world around them:

> The basic reason why [an] actor's definition of [a] situation differs greatly from the objective situation is that the latter is far too complex to be handled in all its detail. Rational behavior involves substituting for the complex reality a model of reality that is sufficiently simple to be handled by problem-solving processes. (p. 151)

Also like Korzybski, Simon (1969) noted that people tended to think in "hierarchies". Thus, if asked to draw a face, a person might start with the basic outline of a face, then proceed to add large features, such as a nose, eyes, and a mouth, and then continue on to add more specific details. And Polyani (1966) suggested that humans' perception of reality was "filled with strata of realities, joined together meaningfully in pairs of higher and lower strata" (p. 35).

For example, a person's understanding of a written paragraph was based on a sequence of understanding about letters, words, phrases, sentences, etc.

Eden (1994) models human decision making as a series of steps that mirrors the sequence of the structural differential (see Figure 3.6). Furthermore, he notes that "[d]ecision making is a consequence of attaching meaning and significance to the events that occur around us – perception filters in data, and construal interprets; thus perception and construal are not the same thing" (p. 263). Though his terminology is different, Eden is clearly pointing out that lower level abstractions (perception) are not the same as higher level abstractions (construal). Thus, Eden's model is highly consistent with Korzybski's process of abstracting.

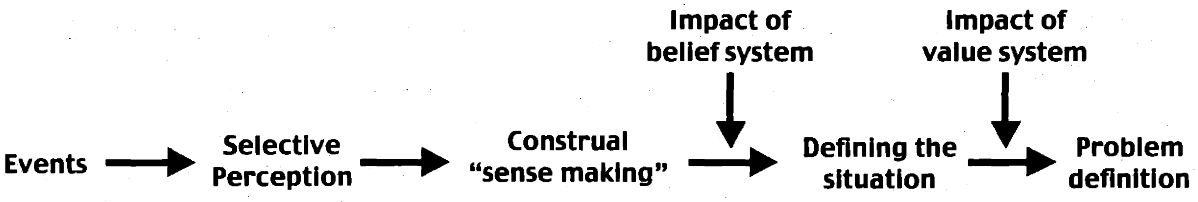


Figure 3.6: Eden's model of human decision making (adapted from Eden, 1994, p. 263).

Other researchers have also made similar observations about people and their abstractions. Senge (1990) observed "leaps of abstraction" (an expression derived directly from Korzybski's theories) during disputes in organizations, when "[w]hat was once an assumption becomes treated as fact," a problem that occurs when individuals "move from direct observations (concrete 'data') to generalizations without testing" (p. 193). Piore et al (1994) used the example of reading a speech to observe that when one reads a speech, one interprets the speech, by adding inflection for example. Consequently, they argued, the read speech is not the same thing as the speech delivered by the original speaker. Finally, Norman (1993) stressed the importance of the process of abstraction, and highlighted many of Korzybski's key points, when he observed:

> The cognitive age of humans started when we used sounds, gestures, and symbols to refer to objects, things, and concepts. The sound, gesture, or symbol is not the thing itself; rather it stands for or refers to the thing: It represents it... The powers of cognition come from abstraction and representation: the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details. This is the essence of intelligence, for if the representations and the processes are just right, then new experiences, insights, and creations can emerge. (p. 47)

3.2.4. The Organism-as-a-Whole and Semantic Reactions

Another essential element of Korzybski's theories is the idea of the "organism-as-a-whole". Korzybski stressed this notion in two respects: the concept of semantic reactions and the importance of total body experiences. First, he rejected the traditional practice of splitting the "mind" or "intellect" from "feelings" or "emotions". Instead, he noted that the human brain operated in a cyclic fashion that started with an emotional reaction to a sensation followed by an intellectual component (see Figure 3.7). The intellectual component then fed back into the emotional component, modifying the emotional reaction. Thus, the two reactions – emotional and intellectual – can not be divided, not unlike the mistaken notion that space-time can be split into "space" and "time".

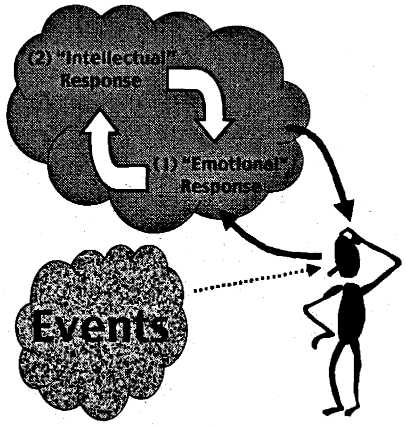


Figure 3.7: The interlocked cycles of "intellectual" and "emotional" responses. A person observes events, triggering (1) an emotional response, which is in turn followed by (2) an intellectual response, which then modifies the emotional response, and so on.

This indivisibility between emotions and intellect led Korzybski to develop a concept he called the “semantic reaction”, which he defined as “the psycho-logical reaction of a given individual to words and language and other symbols and events *in connection with their meanings*, and the psycho-logical reaction, which *become meanings and relational configurations* the moment the given individual begins to analyze them or somebody else does that for him” (Korzybski, 1994, p. 24). Thus, the process of abstracting is not simply a rational, intellectual process, but one that includes emotional responses. More specifically, it includes responses to *meanings*, hence the term “semantic”. Furthermore, a person reacts emotionally not only to the original stimulus (be it an action, object, word, or symbol), but to his own further abstractions based on that stimulus.

This notion helps to explain the emotional elements of inter-group disputes that was previously discussed (see Section 2.2.2). Individuals from different groups attach different meanings to events, words, etc. Such understandings of meaning, however, include both intellectual and emotional elements. Thus, when a person's interpretation of the world is challenged, his or her reaction is likely to include an emotional element.

The conception of the organism-as-a-whole also suggests that a person learns best when as many of her sense are engaged as possible. Therefore, educational methods that engage a student's hearing, sense of touch, and even her emotions, will yield better learning than simple lectures alone. Nonaka and Takeuchi (1995) noted the importance of bodily experience in product development problem solving, as did Carlile (1997). Honda, the automotive manufacturer, institutionalized this concept for problem solving in the factory, requiring the practice of the "3A's": problem solvers must go to the *actual spot*, examine the *actual part*, in the *actual situation* (Nelson et al (1998).

3.2.5. Abstractions and Language

Korzybski's process view of the world and his recognition of the human process of abstraction has several consequences for understanding the use (and abuse) of language. First, Korzybski rejected the object-subject division implied in the "is" identity. For example, one might commonly state, "The grass is green." "Green," however, is a *label* conceived by humans to describe the way an object labeled as "grass" absorbs and reflects light. Thus, one speaks more correctly by saying, "The grass appears green to me". This second version of the statement explicitly recognizes the process of abstracting, and does not assume that "green" is a trait intrinsic to the grass.

In place of a language based on the "is" identity, Korzybski advocated the development of a functional language, one that describes behaviors and processes instead of asserting characteristics. Korzybski argued that such a language was closer to the structure of the world (based on the process view of world). This similarity is essential, because the only link between a language and the empirical world is the relationship between a language's structure and the structure of the world it is intended to represent. The more accurate this relationship, the more useful (and correct) the language.

These ideas have been supported by many other authors over the years. Dreyfus (1981) in explaining Heidegger's theories, noted that "[t]he relationship between me and what I inhabit [my environment] cannot be understood on the model of the relation between subject and object" (p. 45). Instead, Heidegger stressed the importance of understanding the relationship *between* an object and subject – by themselves, neither was complete. Both needed the other for sense to be made of either. Similarly, system dynamics was created as a modeling language specifically to provide a method of illustrating processes and dynamic relationships in place of linear cause-effect languages (Senge, 1990; Sterman, 2000; Weick, 1976).

Given this emphasis on recognizing processes, relationships, and abstractions in place of asserting intrinsic characteristics, Korzybski turned his attention to symbols, the building block of any language. First, Korzybski noted that a symbol is "a sign which stands for something" (p. 78). Understanding what a sign stands for, however, is not as simple a task as it might initially appear. Specifically, Korzybski described symbols, and human words in particular, as "multiordinal". That is, any symbol can take on a potentially infinite number of meanings, and the only way to be certain of a symbol's meaning is to extract that meaning based on the specific context in which the term is used. Thus, Korzybski stated that

> [t]he main characteristic of [multiordinal] terms consists of the fact that on different levels of orders of abstractions they may have different meanings, with the result that they have no general meaning; for their meanings are determined solely by the given context... Accidentally, our vocabulary is enormously enriched without becoming cumbersome, and is made very exact. (p. 14)

The only way to comprehend a symbol's meaning is to understand its relationship to the world it is signifying, hence the importance of a language's structure matching the structure of the world it describes.

Suchman (1990) made almost exactly the same argument, referring to the "indexality" of words, rather than "multiordinality": "... as a consequence of the indexality of language, mutual intelligibility is achieved on each occasion of interaction with reference to the situation particulars [i.e., the "given context"], rather than being discharged once and for all by a stable body of shared meanings" (p. 50). Furthermore, Suchman (1990) also noted that

> [t]he efficiency of language is due to the fact that, on the one hand, expressions have assigned to them conventional meanings which hold on any occasion of their use. The significance of a linguistic expression on some actual occasion, on the other hand, lies in its relationship to circumstances that are presupposed or indicated by, but not actually captured in, the expression itself. (p. 50).

Similarly, Weick (1976) observed that "[i]t's certainly obvious that saying is subject to numerous interpretations" (p. 157), and Dreyfus (1981) stated, "[a] sign's signifying must take place *in a context*, and it signifies, i.e., it can *be* a sign, only for those who *dwell* in that context" (p. 100). Therefore, like a map and the territory it represents, the meaning of a statement can only be understood in terms of its relationship to the events it describes – the more similar the relationship, the more useful the statement.

Furthermore, one's perception of the world is shaped by the structure of the language used to describe the world: " ... every language having a structure, by the very nature of the language, reflects in its own structure that of the world assumed by those who evolved the language... we read unconsciously into the world the structure of the language we use" (Korzybski, 1994, p. 59). Thus, as Dreyfus (1981) stated "there are no interpretation free facts" (p. 31). Similarly, Piore et al (1994) noted that "language pre-organizes the possible ways in which a system of meaning can show up" (p. 418), and Simon and March (1966) stated that "...

the world tends to be perceived… in terms of the particular concepts that are reflected in [a group's] vocabulary" (p. 165). In addition, Henderson (1991) and Carlile (1997) both found that not only do words have strong effects on how an individual perceives the world, but the objects commonly used by an individual (such as blueprints, faxes, tools, etc.) have a similar effect. Therefore, an individual's perception of the world will be strongly influenced by the structure of that person's system of symbols.

3.2.6. Knowledge as Structure

With a conception of language based on relationships, one can now move to a more useful understanding of "knowledge", an understanding that is not dependent on the categorization of different "types" of knowledge. To develop this understanding, one must again turn to Korzybski's concepts of process and order. Given that events (processes) occur in a specific order, it is possible to fashion relationships between them – for example, one turns a key *before* a car engine starts (order), and the act of turning the key starts the engine (relationship). Given a series of relationships, one can construct a *structure*, "a complex of ordered and interrelated parts" (Korzybski, 1994, p. 56) based on those relationships. Put another way, structure is a set of relationships between relationships, and relationships are based on the order of a given set of events. Therefore, structure is an abstraction from relationships, and relationships, in turn, are abstractions from order. Note, then, that any structure that a person sees in the world is an abstraction that exists only in the person's mind, and it is not an actual attribute of the world itself (which is always changing).

Korzybski then described "the content of knowledge" as "structure". The point is that a single, isolated fact is not "knowledge", nor is a simple list of facts. "Knowledge" consists of the construction of *relationships* and *structure* that link facts to one another. An analogy with a house clarifies the concept (Korzybski, 1994): A house is not simply a pile of bricks – it is a set of bricks organized (structured) in a specific fashion. So too with knowledge and facts.

These concepts, also, are supported by other researchers. Lave (1988) states that "... knowledge is not primarily a factual commodity or compendium of facts, nor is an expert knower an encyclopedia" (p. 175). Instead, knowledge is an understanding *between* different concepts. Simon (1969) espoused a similar theory, noting that memory is not based on "pictures" but on relationships: given one fact, a person can recall others based on the relationships between those facts and the one given. More recently, Norman (1993) observed a similar ability and described it as "navigation by description". Thus it seems that the human mind operates on the basis of relationships, not individual, isolated facts, lending support to Korzybski's ideas.

A further consequence is suggested by Korzybski's notion that the "content" of knowledge is "structure": knowledge is *context specific*. As described above, order leads to relations, which in turn lead to structure. Structure, then, leads to *meaning* (Korzybski, 1994) (see Figure 3.8). That is, once a set of relationships are connected to one another creating a structure, meaning can be abstracted from that structure. For example, words alone do not convey meaning. Words must be organized using grammar to create a coherent structure. Once this structure is in place, however, a message can be communicated which has meaning. Given the multiordinality of symbols, the meaning of a given message is context specific. Consequently, what one "knows" is tied to the specific context from which the relationships were originally abstracted.

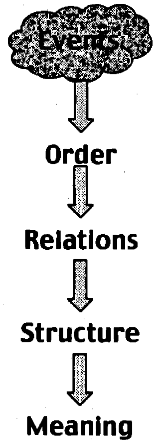


Figure 3.8: The process of abstracting meaning from events.

Other researchers have developed very similar constructs. Giddens (1984) and Suchman (1990) both described actions as "situated", i.e., actions take place ("are situated") in a particular place at a particular time, making any action unique. Lave (1988) used the term "knowledge-in-practice" to connote the specific relationship between what a person does and the context in which it is done to what a person knows. The same type of relationship was implied in Schon's (1992) concept of "knowing-in-action" and Morgan and Ramirez's (1983) "action learning". Dreyfus (1981) also argued that what a person knows only makes sense in context – once a concept is removed from its context, its source of meaning is destroyed.

Lave (1988) provided one of the best examples of this dynamic, context specific nature of knowledge. He investigated the use of mathematics by adult students in everyday situations and compared its use under those conditions to how they were taught math in schools. In school, mathematical concepts tended to be taught divorced from any specific application: 1+1=2, for example. Outside of the classroom, however, the students routinely applied mathematical principles, but in different and dynamic fashions. When shopping for their families at the supermarket, for example, students were forced to estimate the number of meals they were likely to make before their next trip to the market, consumption rates for the various items they were purchasing, and a host of other factors. The researchers found that the mathematical relations used under these conditions bore little resemblance to the context-free math taught in the classroom. These observations then led to the concept of "knowledge-in-practice", e.g., how knowledge of mathematical principles was used in a particular context or practice to solve a problem.

Finally, given that knowledge is linked to meaning, knowledge is also linked to standards of *evaluation* (Korzybski, 1994). Thus, one not only "knows" *how* to do something, one also knows how to do that something *correctly*. Similarly, what one "knows," one "knows" is "the truth". Recalling the notion of the semantic reaction, belief in "the truth" or what is "correct" is not simply an intellectual reaction, but an *intellectual-emotional* reaction. Therefore, "[t]he stronger the structural 'belief' in the 'truth' of the representation, or, in other words, the more we identify the higher order abstractions with the lower, which, in fact, are different, the more dangerous becomes the 'emotional' tension in the factors" (Korzybski, 1994, p. 198).

This connection between knowledge of "the truth" or what is "correct" and emotional reactions has become increasingly recognized in the management literature. Allen (1988), for example, observed in his studies that "[a]n engineer's prestige among his colleagues is founded to a great degree upon an almost mythical characteristic called 'technical competence'" (p. 193). Similarly, Wenger (2000) noted that "[k]nowing… is a matter of displaying competencies defined in social communities" (p. 226). When an engineer appeared to lack knowledge of a topic or to be uncertain of a technical issue, his peers were likely to perceive his ignorance as a lack of technical competence, and, consequently, that engineer's prestige would be diminished.

Thus, it became important for an engineer to be definitive in his knowledge, and to staunchly defend his perspective in technical disputes.

Similarly, Lave (1988) describes a problem as “a dilemma with which the problem solver is emotionally engaged” (p. 175). That is, if the problem solver did not care about the dilemma or its consequences, she would not have a problem – the dilemma could simply be ignored. For the problem solver to devote time and energy to addressing the issue, she must have some emotional stake in its outcome. Carlile (1997) observed this same behavior in his study of product development teams: designers would argue fiercely that a decision must be made in one direction, while manufacturing engineers would argue just as fiercely that a different direction had to be taken. Because their prestige (as it relates to their perceived technical competencies) was at stake, as well as their “correctness” about the design decision (not to mention opportunities for promotion and pay increases), the designers and manufacturing engineers were emotionally engaged in the decision. Thus, Carlile (1997) observed that knowledge is not neutral, but is instead “‘charged’ with power”. Korzybski’s notion of the semantic reaction, coupled with the process of abstracting, helps to account for these aspects of knowledge.

Finally, it should be noted that such emotional disagreements in organizations are not necessarily based on malicious intent, but on a desire to do what is best for the organization. Each group is concerned with slightly different aspects of a problem, and, consequently, each group will advocate different recommendations (Dougherty, 1992). The resulting conflict, then, does not originate from people’s small-mindedness per se, but from “honest people believing they know what is best for the organization” (Eden, 1994, p. 260).

3.2.7. The Individuality of Abstractions, Mental Models, and Confusing Orders of Abstraction

Given all of the above discussions, one can state that most disputes between people are the result of the *different abstractions* held by the people involved in the dispute. Returning again to one of the foundational premises, all "objects", including humans, are dynamic, changing processes. Thus, no two people are the same, nor is one person exactly the same at two different times. Consequently, the details and inferences one person abstracts from an event will always be different from those of another person, or of that same person at a later time. Therefore, "[w]e can only *agree* on colours, shapes, distances, [etc.], by ignoring the fact that the effect of the 'same' stimulus is different on different individuals" (Korzybski, 1994, p. 375). What one person sees as "green" is not exactly the same as what another person sees. Since abstractions occur inside people's heads, only by pointing to something that is "green" can two people agree on what the word "green" represents – they have no other way of comparing their impressions or abstractions (Korzybski, 1994). Korzybski referred to this process of "pointing to the thing" as "silence on the objective level" – since words are not the thing, the only way to be sure that two people are discussing the same thing is to point to it.

Furthermore, a person's past experiences will influence what new perceptions are received, and, consequently, what new abstractions she will be capable of making (Korzybski, 1994). Thus, Korzybski distinguishes between an "ideal" observer and an "imperfect" one. Consider first the ideal observer (Figure 3.9). At some initial time, Time 1, the person observes several events, represented by the geometric shapes in the figure. Based on these events, the person abstracts descriptions (*a*, *b*, *c*, and *d*), suggesting a conclusion or inference (*A*), and causing the person to take an action (*A'*). Then, at a later time, Time 2, the person witnesses another event, related to, but different than, the initial events (represented by the shaded triangle in the figure). The ideal observer ignores her previous inferences and conclusions, and generates a new one (*B*) based on the new set of descriptions (*a*, *b*, *c*, *d*, and the new *x*). This new conclusion then leads the person to carry out a new action (*B'*).

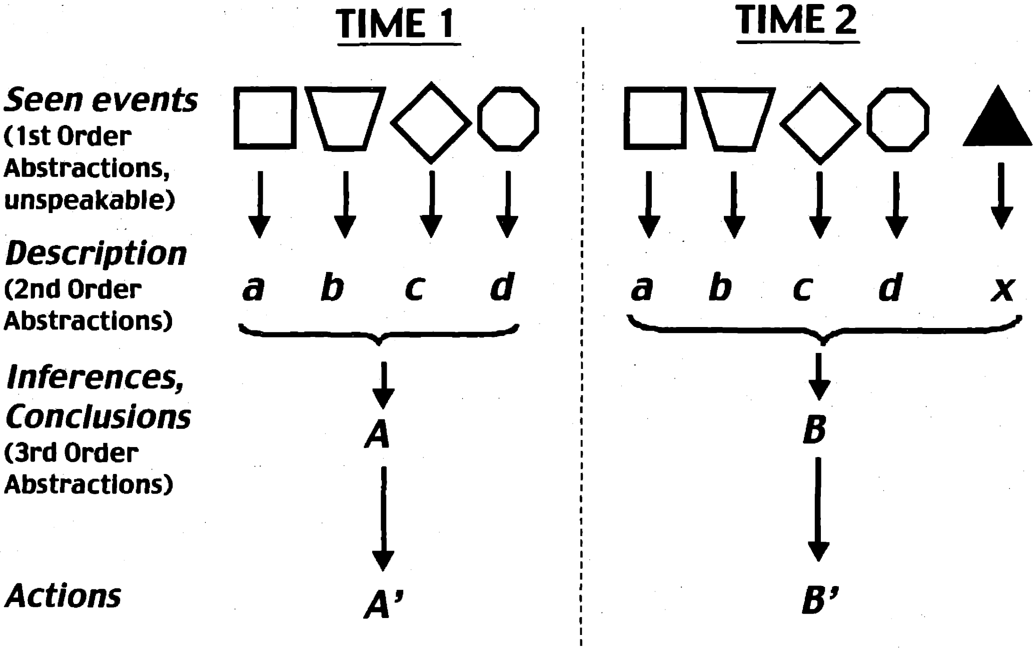


Figure 3.9: The abstraction processes of an ideal observer. When new information is received, the ideal observer interprets all of her old information again along with the new. (Adapted from Korzybski, 1994).

The abstraction processes of an imperfect observer, in contrast, are markedly different (Figure 3.10). As in the case of the ideal observer, the imperfect observer witnesses an series of events at Time 1, leading to descriptions, suggesting conclusions, and then resulting in an action. The results at Time 2, however, reveal the differences. When the new, related event is observed (again represented by the shaded triangle), the imperfect observer replaces the lower order descriptions of the previous events with a higher order abstraction, his old conclusions, *A*. He then uses this conclusion to interpret the new event [*A(x)*], leading to a new description, *y*. Consequently, another set of conclusions and inferences are drawn, *C*, resulting in a different set of actions, *C'*.

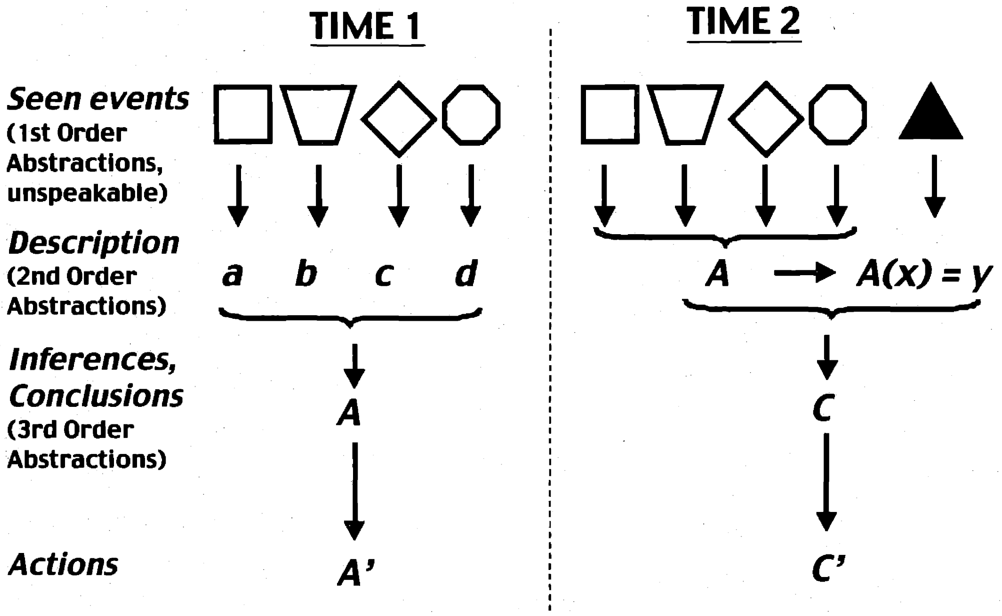


Figure 3.10: The abstraction processes of an imperfect observer. When new information is received, the imperfect observer interprets that information using the conclusions drawn from the old information. (Adapted from Korzybski, 1994.)

The important distinction between the ideal and imperfect observers, then, lies in how they use and compare the information they receive. The ideal observer always reevaluates all of the old data along with the new, and then uses that enlarged dataset to draw her conclusions. The imperfect observer, on the other hand, simply interprets any new data using conclusions drawn from the old data. The imperfect observer will do this even if the new data contradicts the conclusions drawn from the old data.

As with the issues surrounding multiordinal terms, there are both benefits and drawbacks to the abstraction processes of the imperfect observer. As noted above, the principle drawback is that the imperfect observer is unlikely to update his conclusions to better match his objective reality, even if he receives information that would allow him to do so. On the other hand, the imperfect observer's abstraction process allows for some efficiency: rather than having to review every detail of a situation, place, object, or person every time he encounters it, the imperfect observer can rapidly recognize the event as one he has encountered before.

Other researchers have referred to the processes represented by the imperfect observer using a variety of terms. Lambert and Lambert (1964), in there review of social psychology experiments, defined an attitude as "an organized and consistent manner of thinking, feeling, and reacting with regard to… any event in one's environment" (p. 50). Using the terminology shown in Figure 3.10 for the imperfect observer, an attitude is represented by $A(x)$. As illustrated in the figure, Lambert and Lambert (1964) suggested that a person was more likely to accept information that was consistent with his existing attitudes – the person would take in information and make it conform to his preexisting conceptions of the world. Weick's (1976) studies of organizational behavior led him to a similar set of conclusions, noting that people tend to find order in chaos where they expect to find it or tend to notice things that will help them achieve what they want to achieve. A variety of terms are now used to describe such selective observing and filtering, such as "mental models" (Leonard-Barton, 1995; Senge, 1990) "interpretative schemes" and "thought worlds" (Dougherty, 1992), and "knowledge structures" (Walsh, 1995).

The most troublesome aspect of the imperfect observer's processes, however, relate to what Korzybski refers to as "confusing orders of abstraction". Simply put, people tend to confuse higher order abstractions with lower ones, such as, replacing the lower order abstraction that "his face appears red" with the higher order abstraction that "he is mad", without taking the time to discover that his face appears red because he had just been running.

Simon and March (1966) noted this tendency in organizations, observing that "evidence is replaced with conclusions drawn from that evidence, and these conclusions then become the 'facts' on which the rest of the organization acts" (p. 155). Simon and March coined the term "uncertainty absorption" to refer to this process: "when inferences are drawn from a body of evidence and the inferences, instead of the evidence itself, are then communicated" (Simon and March, 1966, p. 165). Similarly, Schein (1992), during his studies of organizational culture, found that "[m]ost communication breakdowns between people result from their lack of awareness of that in the first place they are making basically different assumptions about meaning categories" (p. 72). That is, people tended to end up in arguments because they were actually disagreeing on the meaning of the words they were using, rather than the conclusions or inferences they each held.

Schein's observation leads directly to another important element of Korzybski's theories: having a "consciousness of abstracting", or an "*awareness* that in our process of abstracting we have *left out* characteristics" of the objective world (Korzybski, 1994, p. 442). For people to communicate effectively, they must first be aware that they may be defining words differently, observing different aspects of the same event, or abstracting different meanings from the events they see or words they use. Once this awareness has been achieved, a person is more likely to ask for clarification of another person's statement before reacting to it, in order to be sure that she and the other person are abstracting the same meaning from the words being used (Korzybski, 1994). Such pauses for clarification then facilitate more effective and productive communication.

Lawrence and Lorsch (1967) seemed to be advocating just such an approach when they endorsed "confrontation" as a means of settling conflicts. During their studies of organizational dynamics, the researchers noticed that some organizations tended to ignore problems, others simply allowed their members to argue endlessly, while others forced the participants in the dispute to *explain* their point of view and the reasons behind that point of view. Lawrence and Lorsch termed this approach "confrontational", because it forced the disputing parties to directly confront the underlying reasons for the dispute, rather than simply debating preferred solutions. Furthermore, the study revealed that organizations that used this style of problem solving tended to be among the higher performing organizations than organizations using other methods (or none at all).

Similarly, Keeney (1994) noted that people tend to argue over preferred alternatives, arguments that often end with high levels of dissatisfaction among all of the participating groups. Keeney suggested that this style of debate is reinforced by the manner in which most people approach problem solving: developing alternatives first, and then creating evaluation criteria second. Once alternatives are developed, however, individuals will almost instantly express a preference for one over another. Consequently, when the debate begins over selection criteria, people will argue in favor of criteria that will make their preferred alternative appear better and the other options appear worse. Instead, Keeney argued, problem solving should begin with the selection of evaluation criteria. Once the criteria are selected, alternative problem solutions can be created and then evaluated. Since the participants agreed on the evaluation criteria in advance of the creation of alternatives, they are more likely to accept the alternative suggested based on the evaluation.

3.2.8. Alternative Model of Communication

Earlier, it was argued that a critical assumption of the information processing framework was its reliance on stable and shared meanings for the symbols used to communicate. As discussed above, however, the reality of human communication is that such shared definitions do not necessarily exist in advance. Instead, because of the multiordinality of language and the context specific nature of knowledge, the definitions are created over the course of any given human interaction. Lave (1988) therefore describes cognition as a "distributed" process – a person's understanding of a situation does not come solely from within that individual, but is instead a product of that individual's own thoughts and her interactions with other members of society (Eden, 1994; Henderson, 1991; Lave, 1988).

Furthermore, because of the emotional content of all knowledge, the "information flow" is not neutral. Instead, all knowledge is laden with definitions of "value" and "preference" and "correctness". Consequently, even in "intellectual" realms such as engineering, emotions come into play and assumptions of rationality quickly fail. The information processing framework offers no mechanism for handling such problems.

Figure 3.11 illustrates the problems discussed above and clarifies their origins. Two imperfect observers, *A* and *B*, both witness an event that possesses an infinite number of characteristics. Biased by their past experiences, each person abstracts a different set of objects from the event, followed by descriptions. Because the objects and descriptions abstracted by each person are different, each also abstracts different conclusions and inferences from the event they witness. *A* then tells *B* his conclusions. Several problems are then confronted. First, because the process of abstraction is a process of summarizing and omission, the message *B* abstracts from *A*'s signal is not exactly the same of the message *A* intended to send.

Furthermore, when *B* compares *A*'s conclusion to his own, he realizes that *A* is "wrong" – *A*'s conclusions in no way resemble his own. This discrepancy triggers an intellectual-emotional (semantic) reaction, and an argument is likely to ensue.

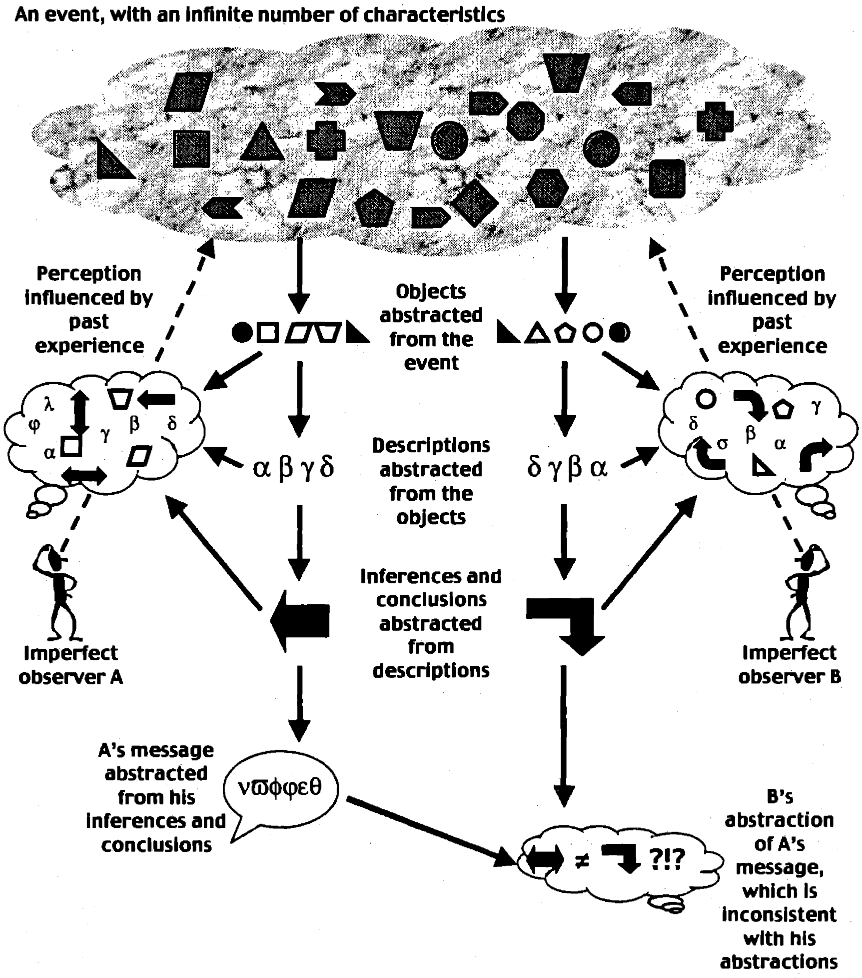


Figure 3.11: A depiction of why the information processing framework does not apply to humans.

Given these problems, a new model must account for the dynamic, multiordinal, distributed, and value-laden nature of communication. That is, Korzybski's concepts of abstracting need to be combined with an interactive model of human communication. To do this requires the introduction of the "double interact".

The double interact is a framework for human communication developed by Weick (1976). Depicted in Figure 3.12, the double interact clearly illustrates the mutual dependence between two people when they are communicating. Given a conversation between two individuals, Person A and Person B, A will first speak to B – the first action. B will then respond to A, the first *interaction*. Based on B's response, A will respond again, resulting in the *double interact*. This back-and-forth element of communication is important, because, as Suchman (1990) noted, a person cannot know for certain what message she has sent until she sees how another person responds.

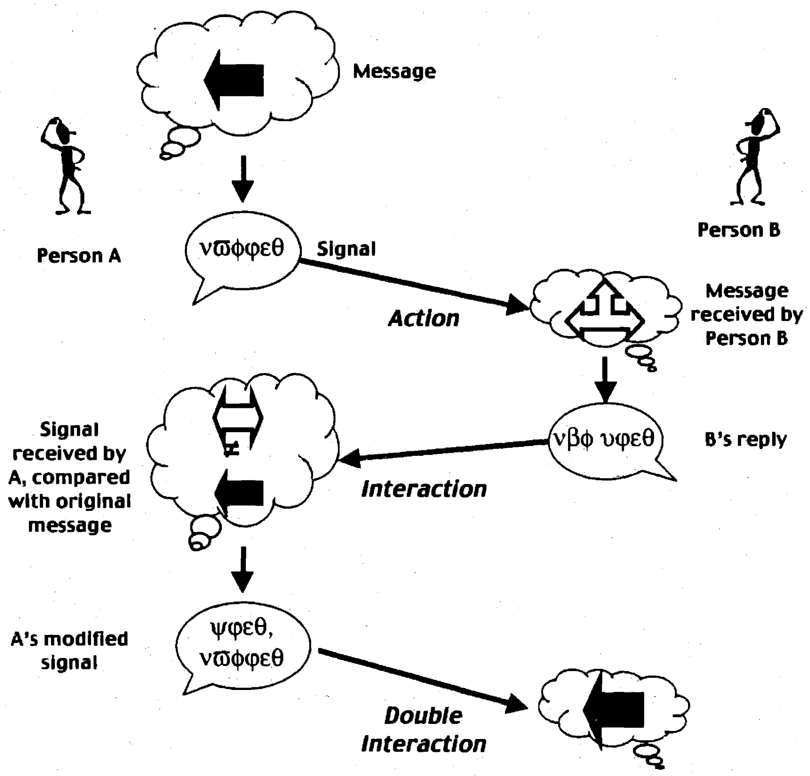


Figure 3.12: Weick's "double interact" model of communication.

Weick's double interact, however, can be enhanced when combined with Korzybski's theories. The result is depicted Figure 3.13. As in Figure 3.11, the communication process begins with two imperfect observers, *A* and *B*. Each abstracts his own set of objects from the event, followed by descriptions and then conclusions and inferences. *A* then speaks to *B* – the action. *B* abstracts from *A*'s words what he thinks *A*'s conclusions were. *B* then responds to *A*'s message, asking for clarification – the interaction. *A* can then attempt to understand what *B* understood from his (*A*'s) original signal. Based on this understanding, *A* speaks again (the double interaction), adding further explanations to allow *B* to create an abstraction that is closer to *A*'s original conclusion.

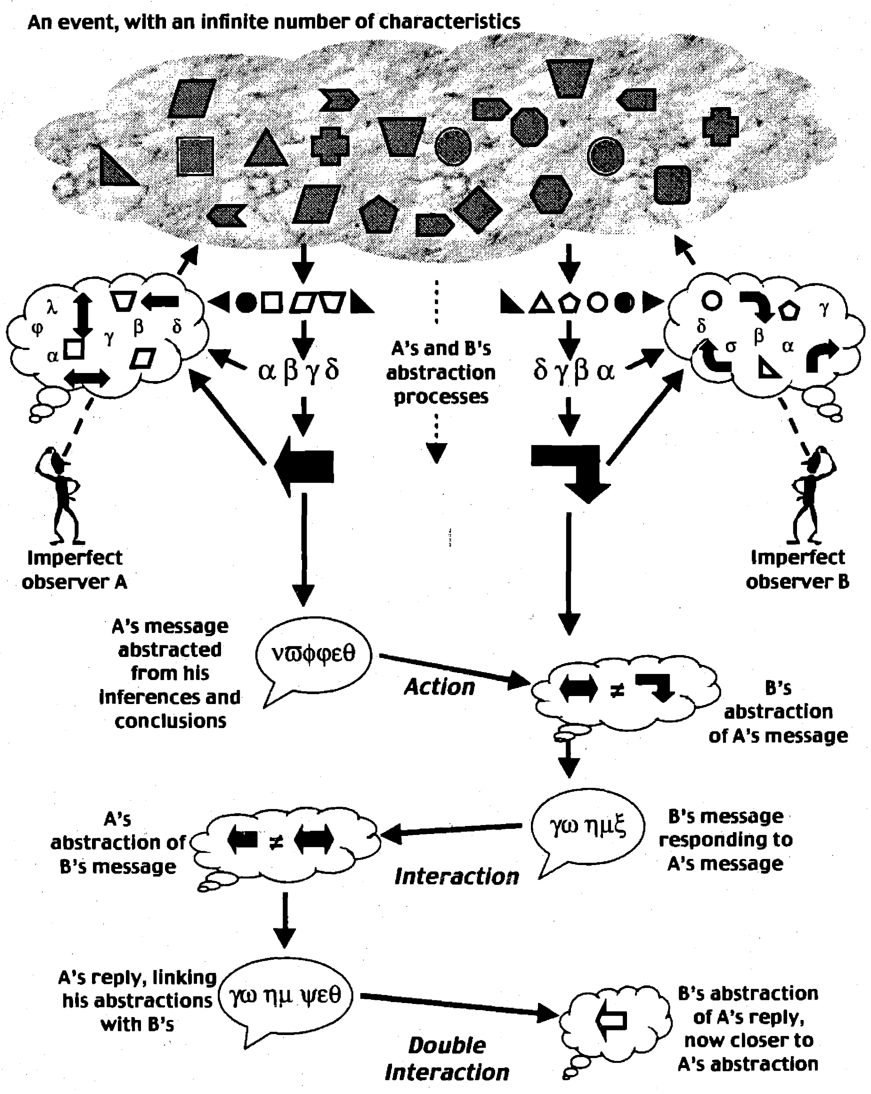


Figure 3.13: The double interact combined with the process of abstraction.

The above model captures all of the elements of communication that can make it so difficult. First, it illustrates the process of abstraction, leading to semantic reactions (intellectual-emotional responses) and indicates that the abstraction process is "biased" by a person's past experiences. Furthermore, the abstractions created by each person are different and unique. Consequently, the individuals do not share the same meaning and definitions for the symbols they use. Therefore, communication between the individuals must be interactive – it must be a continuous process of sending signals, receiving feedback and adjusting messages in order to actively create a shared understanding between them. This model, while more complicated than the information processing framework, provides a more accurate picture of human communications and interactions.

3.3. Review and Summary

Given the breadth of topics covered in the last two chapters, a summary is worthwhile:

1. This review began with the development of a **definition for a system**. Based on literature sources, the following definition was put forward:

> *A system is defined as a set of two or more interrelated elements of any kind working together for a common purpose that satisfies the following three conditions:*
>
> *1. The properties or behavior of each element of the set has an effect on the properties or behavior of the set taken as a whole.*
>
> *2. The properties and behavior of each element, and the way they affect the whole, depend on the properties and behavior of at least one other element in the set. Therefore, no part has an independent effect on the whole and each is affected by at least one other part.*
>
> *3. Every possible subgroup of elements in the set has the first two properties: each has a nonindependent effect on the whole. Therefore, the whole cannot be decomposed into independent subsets. A system cannot be subdivided into independent subsystems.*

2. Given this definition of a system, the next task was the creation of a definition for **integration**. That definition was given as:

> *The process of combining a set of elements such that together they exhibit properties not exhibited by any element independently.*

3. Various studies related to integration were then reviewed, illustrating the importance of the concept. Typically systems that are "better integrated" have higher performance than less well-integrated systems. Furthermore, integration processes play important roles in innovation and market creation, particularly in the development of architectural innovations.

4. The concepts of **differentiation** and **integration**, as they apply to organizations, were then discussed. For a variety of reasons, ranging from managing complexity to personal interests, the individuals and subgroups within an organization tend to *differentiate* themselves, that is, tend to specialize their skill sets and knowledge bases. The creation of successful products or delivery of quality services, however, requires that these differentiated elements be *integrated.* The integration process is complicated by the effects of differentiation, which tends to lead to subgroups with different world-views and "languages."

5. Theories of communication and knowledge were discussed to provide a conceptual framework to help understand the problems associated with differentiation and to indicate potential methods to address integration. The **information processing** framework was introduced but then rejected, because its assumption of stable and shared categories of meaning proved to be inaccurate.

6. In place of the information processing model, Korzybski's **theory of abstraction** was introduced. This theory argues that human beings *abstract* from their environment and that since every human being is unique, each person's abstractions will be different. Consequently, the meaning of symbols, as well as "knowledge", becomes context-specific. Furthermore, the intellectual and emotional components of a person's abstractions cannot be split, so that "knowledge" includes value definitions, as well as judgements about "right" and "wrong". The

process of abstraction was then combined with the **double interact** to illustrate a new framework for communication processes.

With these theoretical foundations in place, the next chapter explores the development of the hypotheses for this study, as well as the experimental techniques that were used.

4. HYPOTHESIS FOUNDATIONS AND EXPERIMENTAL METHODS

Given the above discussions of differentiation, integration, and communication, the central problem to be addressed by this research was to improve the ability of product development organizations to integrate knowledge from multiple disciplines. This chapter will establish the hypotheses and experimental methods used in this study to achieve that goal. First, integration tools and methods identified by other researchers will be reviewed. Then, based on those previous investigations and the communications model developed above, three hypotheses will be postulated and explained. Finally, the experimental method used to test these hypotheses will be described.

4.1. Integration Tools and Techniques

Integration methods identified in the literature can be grouped into two overarching strategies. First, researchers have identified a variety of organizational designs that facilitate integration in different ways. Second, other studies have identified specific practices that can facilitate integration, regardless of an organization's structure. Both types are reviewed below.

4.1.1. Organization Design for Integration

At a top-level, the entire organization must shape itself to best facilitate integration between its parts. The literature cites two basic poles from which to choose: a functional or a product organization. A functional organization is one in which engineers and other specialists are grouped together within their specific domains of knowledge, such as mechanical engineering, manufacturing, or sales. A product organization, on the other hand, groups employees not according to their skills, but according to the project with which they are involved. In general, a functional organization tends to retain and disseminate knowledge well over the long term, and during times of stability (Allen, 1988; Burns and Stalker, 1961; Nonaka and Takeuchi, 1995). A product organization, on the other hand, tends to perform better in dynamic environments and when a high degree of integration is required (Allen, 1988; Burns and Stalker, 1961; Nonaka and Takeuchi, 1995).

Between these poles, authors have recommended a variety of options. One common concept is the matrix organization, in which engineers are first organized into specialty groups, and then assigned to product teams for specific projects (Allen, 1988; Clark and Fujimoto, 1991). Nonanka's and Takeuchi's (1995) "hypertext organization" and Van de Ven's (1986) "holographic organization" are similar concepts. The general idea is to allow the functional structure to exist to maintain people's specialty skills over the long term, while facilitating the required flexibility and integration needed on specific projects with product teams.

4.1.2. Tools and Practices for Integration

Whatever the organizational structure for the entire company, a variety of mechanisms exist for integrating people at a more individual level.

Co-Location

Several studies have shown that by co-locating engineers, the performance of the development projects on which they work improves (Allen, 1988; March and Simon, 1966). By facilitating face-to-face communication, co-location helps engineers develop a shared language and allows them to slowly reveal their tacit assumptions to one another. Engineers then develop a shared frame of reference, improving their ability to communicate, which in turn improves their ability to develop an integrated product design.

Human Bridges

Whether development groups are co-located or not, studies have shown that in general, humans are the best mechanisms for transferring knowledge. Studies by Roberts (1988) and Nishiguchi and Beaudet (1998) demonstrate that engineering groups can achieve high performance by moving engineers between functional groups or companies to exchange ideas and knowledge in face-to-face meetings. Furthermore, such human bridges also best facilitate the transfer of knowledge between projects over time, as studies by Cusumano and Nobeoka (1998) and Aoshima (1996) have illustrated.

Teams

Several studies have indicated that project or product teams also tend to perform better than organizations that only have functional structures (see for example, Womack et al, 1991). Of particular benefit appear to be "heavy weight" teams (Clark and Fujimoto, 1991). These are teams that include nearly all of the skills and resources needed to complete a project from beginning to end, usually led by an experienced manager. Because they are relatively self-contained, these teams often achieve a high level of integration in their work. Moreover, due to their autonomy, such teams can often be self-organizing, configuring themselves specifically for the task at hand, further improving their level of integration (Imai *et al*, 1985; Nonaka and Takeuchi, 1995).

Gatekeepers

The concept of the gatekeeper was first proposed by Allen (see Allen, 1988). Gatekeepers are individuals who have contact with a number of subgroups within an organization and outside of it. These individuals are then in a position to move information between groups, translating between different functional languages as needed. Roberts (1988) extended the idea of the gatekeeper beyond the technical role originally noted by Allen, identifying manufacturing and marketing gatekeepers as well.

Integration Teams

In their study of project performance, Lawrence and Lorsch (1967) noted that the presence of an integration team tended to improve a project's results. Such teams were tasked to and rewarded for moving between the different specialty groups, ensuring that data needed by one group from another was supplied, and that it was supplied at the right time and in the proper fashion. Thompson (1967) and Roberts (1988) also found evidence supporting the benefits of such teams.

Burns and Stalker (1961), however, found that the presence of such integration teams can also hurt performance. While the teams may facilitate the transfer of information between groups, they do so without putting the two groups directly in contact. As a consequence, the two groups never improve their understanding of each other, potentially allowing for negative stereotypes to persist and be reinforced. Thus, integration teams are a technique that must be used with care. They may prove helpful in the short term, but unless the proper actions are taken to ensure good direct relations between groups, the indirect relationships established through the integration team could lead to a deterioration in performance in the long term.

Management Leadership

Another factor that has been shown to have a significant impact on project performance is management leadership and skill. Lawrence and Lorsch (1967) found that teams with the highest performance were managed through "knowledge-based influence," in which a manager's instructions were followed not only because of the manager's hierarchical status but also because the manager was respected for his or her knowledge. The SAPPHO studies (Rothwell *et al*, 1974) also demonstrated the importance of management in project success. Those investigations revealed that key individuals in successful projects tended to be more experienced and have more authority than key individuals in failed projects. Furthermore, the SAPPHO studies concluded that many project failures could be attributed to avoidable management mistakes, adding more weight to the importance of good management for project success. Similarly, Imai *et al* (1985) found that management's role as a project "catalyst" was important. They also noted that management's ability to use "subtle control," the careful balancing of explicit instructions and ambiguity, distinguished high performing companies from low ones.

Confrontational Problem Solving

Another element of management leadership is the use of confrontation problem solving (Lawrence and Lorsch, 1967; March and Simon, 1966). Rather than allowing problems to fester unresolved, or, at the other end of spectrum, attempting to force compromise solutions on people, managers of highly successful teams tended to address problems in the open. People with conflicting opinions were allowed to voice those opinions, and then, rather than seeking a compromise, data was collected to support a specific solution to the problem. Once data was available, even people who still did not necessarily favor the answer were found to support it.

Rules and Procedures

In a relatively stable environment, rules and procedures can be another useful technique for integration (Galbraith, 1973; March and Simon, 1966; Roberts, 1988). By establishing specific routines, people can know in advance what is expected of them, and how they are to deliver information to other groups. Formalized processes can, therefore, reduce the need for communication within the organization and foster better understandings between groups.

Common procedures can also be used to overcome cultural differences, whether they are related to a field of specialization or national origin. Honda, for example, trains all of its employees worldwide in the same basic problem solving approach (Nelson *et al*, 1998). When engineers from different divisions, or even different countries need to work together, their shared procedures ease the communication burden they face.

Overlapping Phases

Another technique that has been shown to improve performance is overlapping of development phases. Studies by Imai *et al* (1985) and Clark and Fujimoto (1991) have demonstrated that projects that have some degree of overlap between their stages – such as between development and design, design and manufacturing, etc. – tend to perform better than projects that progress in purely sequential fashion. Furthermore, research by Cusumano and

Nobeoka (1998) has shown that overlapping *between projects* can improve the performance of a follow-on development project.

Considering Sets of Design Alternatives

Several studies have suggested that considering sets, or groups, of design alternatives can facilitate problem solving on cross-functional design teams (Liker et al, 1996; Sobek, 1997; Sobek et al, 1998; Ward et al, 1995). Given that the members of a design team are likely to focus on different aspects of a problem, they will each develop a solution that addresses their own needs. Thus, by communicating about sets of potential solutions, engineers both illustrate their goals and demonstrate the range of solutions that would facilitate meeting these goals. Sharing this range of possibilities facilitates problem solving by allowing engineers from different specialties to illustrate the constraints that they face. By gaining a better of these constraints, the specialists can more readily accommodate each other's needs, yielding a solution that is acceptable to the entire team.

Prototypes and Boundary Objects

The final set of mechanisms that can be used to integrate knowledge across functional groups are physical and virtual representations of design problems. Research by Noehren (1999), Aoshima (1996), Carlile (1997), Henderson (1991), Leonard-Barton (1995), Robertson and Allen (1993), and Wheelwright and Clark (1992) has shown that prototypes are excellent mechanisms to facilitate team discussion and focus efforts on problem solving. Prototypes help specialists from different groups share their ideas by allowing for the creation of shared languages, based specifically on the models themselves, rather than idiosyncratic references particular to only to one group. More than simply allowing for the validation of design features, therefore, prototypes are important for their role as *communication tools*. Given their ability to help move knowledge between organizational groups and boundaries, some researchers refer to prototypes and similar artifacts as "boundary objects" (see, for example, Henderson, 1991 and Carlile, 1997).

4.2. Topic Refinement, Context of Study, and Hypotheses

Given all of the above potential topics for further study, it was decided that the most promising would be to study the use of prototypes and other design tools in facilitating integration between disciplines. As noted above, a variety of studies have illustrated the significance of such objects in improving communication. Furthermore, theoretically, the use of objects during cross-discipline communication should be significant benefit. As discussed in Section 3.2.7, since the abstractions a person creates from the environment exist only in that person's head, the only way for two people to ensure that they are both referring to same object is to point to the object. Therefore, in engineering design, the use of models – either physical or virtual – should reduce the uncertainty of communication between groups by facilitating the creation of shared symbols and definitions for those symbols.

4.2.1. Context of Study: Design Problem Solving

With the goal of investigating the use of models and prototypes during product development, the next decision was one of scale. For example, one might investigate the overall use of such models over the course of an entire product development process. On the other hand, specific instances of model usage could be studied. For purposes of this investigation, the specific instance path was chosen. Several factors contributed to this decision.

First, other investigators have determined that problem solving behavior at small scales can be a good indicator of behavior at larger, project-level scales. For example, Iansiti (1998) studied 61 cases of problem solving efforts on design teams. The problems were relatively narrow in their scope, e.g., fixing a problem with a particular component, not designing an entire product. Iansiti (1998) found that a design team's practices at this small-scale level "appeared to have an enormous impact on product and project performance" (p. 102). Therefore, a team's effectiveness in solving small-scale design problems can provide an indication as to its success in addressing the total design problem with which it is confronted.

Furthermore, studying specific cases of problem solving allows for use of the "critical instant" technique (Allen et al, 1978). This method forces study participants to recall a specific event rather than describing "typical behavior". Because of this focus, critical instant methods can be more reliable and accurate than approaches that ask for general behavior. Thus, from both a theory and methods standpoint, studying specific cases of design problem solving appeared to offer the greatest opportunity for meeting this project's goals.

4.2.2. Hypotheses

With a research context determined, a series of hypotheses were developed to explore the use of models and prototypes during engineering problem solving. Using the theoretical foundations discussed in Chapter 3, three hypotheses were generated. These hypotheses are presented in their general form below; they are operationalized (linked to specific, measured variables) in following sections.

Hypothesis One: *Engineers from different specialties interpret a design problem differently.*

Given the theory of abstraction, individuals interpret the world around them in individual ways. Furthermore, as individuals in a specialized engineering group work together, the group will develop its own biases in its interpretations of design problems. Consequently, engineers from different groups will have different interpretations of a design problem.

Hypothesis Two: *Engineers need to broaden their problem interpretations to solve cross-disciplinary problems.*

Given that engineers from different disciplines interpret (abstract) a design problem differently, it is hypothesized that solving the problem to the satisfaction of all of the involved engineers requires each engineer to incorporate aspects of other people's interpretations of the problem into her own. Once an engineer appreciates what aspects of a problem are important to another engineer she can begin to address those issues. Consequently, one would expect that the more similar two engineers' descriptions of a design problem were, the more effectively they were able to solve the problem.

Hypothesis Three: *Tools which illustrate* constraints *and* requirements *facilitate this interpretation-broadening process better than tools that simply generate or illustrate answers.*

Given that engineers interpret design problems differently, they are likely to reach different conclusions about how to solve the problem. Since they are abstracting different "problems" from a given set of events, the solutions to one abstracted problem are not likely to be the same as another. Therefore, tools, such as prototypes or computer modeling programs, that help engineers from one specialty illustrate to another group what problem they are solving are hypothesized to be more effective than tools that simply illustrate answers to a problem.

4.3. Data Collection Approach

A case interview approach was developed in order to collect data to test the above hypotheses. The approach called for individually interviewing engineers and asking them to each describe two cases of problem solving that involved a dispute between different specialty groups. One case was to be what they considered to be an example of an "easy" problem, and the other an example of a "difficult" problem. Interviewees were instructed that the relative ease of the problem need not refer only to the technical aspects of the problem, but could also relate to the social or political factors that came into play. Therefore a "difficult" problem could have been one in which the technical issue was relatively simple, but because of the people or political issues involved, resolving the issue was difficult.

Whenever possible, efforts were made to collect paired interviews for each case. That is, if a design engineer provided a case, he was asked to identify another individual from a different specialty group (such as manufacturing) who also participated in the events. That second individual was then interviewed, using the same set of questions asked of the first person.

Each case interview essentially consisted of two phases. During the first phase, the interviewee was asked a series of open-ended questions intended to draw out a description of the interviewee's interpretation of the problem and the process used to solve the problem. The second phase of the interview used a series of 7-point Likert scale questions to collect outcome measures and demographic information. The following sections detail each question.

4.3.1. Process-Focused Questions

A series of open-ended questions were used to develop a basic description of each design problem that was studied, along with a detailed understanding of what the interviewee considered to be important about the problem and the process that was used to resolve the problem. Following are the questions asked during each interview, along with a brief discussion of the logic behind the question.

Please briefly describe the initial situation – what was the problem?

The purpose of this question was to develop an understanding of the basic context of the problem solving effort – what the technical issue was, what stakeholders were involved, etc. Furthermore, this question often led the interviewee to provide an overall description of the entire problem solving effort, providing useful guidance for tailoring later questions.

What design *factors or criteria were most important to you personally? What criteria or metrics did you use to evaluate the relative benefits or drawbacks of potential solutions?*

In order to directly address the first hypothesis ("engineers from different specialties interpret a design problem differently"), each interviewee was asked to provide a brief list of the criteria he/she used to evaluate potential solutions to the problem (such as "weight" or "performance" or "cost"). As will be discussed below, in cases for which paired interviews were obtained, a comparison of each interviewee's criteria clearly revealed the different priorities each had regarding solving the problem. In addition, this comparison addressed the second hypothesis (engineers need to broaden their problem interpretations to solve cross-disciplinary problems).

How was the problem finally resolved? What was the solution to the problem?

Often tailored based on information generated by the initial question, this question focused the interviewee's attention on describing the *process* the group used to resolve the issue. Thus, interviewees would often outline a series of steps that the team went through to select a solution to the problem, such as: holding a series of meetings, then conducting an experiment, and then developing a solution.

What specific events do you believe were most important in reaching a solution?

Used as a follow-up to the previous question, this question fulfilled two functions. First, it acted as a check to ensure events or steps that seemed to be emphasized earlier actually were considered to important by the interviewee. Second, it prompted the interviewee's memory for further important details. Answers to this question helped to address the third hypothesis ("tools which illustrate constraints and requirements facilitate this interpretation-broadening process better than tools that simply generate or illustrate answers") by prompting participants to describe *how* different tools came into play while solving the problem.

Were any tools (such as drawings, CAD models, prototypes, etc.) useful in reaching a consensus?

This question served as a check of the previous one and explicitly focused the interviewee's attention toward the use of different design tools and their importance (or lack thereof).

Was any one person most responsible for developing the solution or in helping to generate a consensus?

This question was added to the interview after the first two interviews, during which interviewees highlighted the contributions of specific individuals – an engineer who had a particular insight, or a team member who helped to pull the group together.

How many design alternatives did you consider in attempting to resolve the problem, and how were those alternatives considered: in series, in parallel, etc.?

Based on some of the trends indicated in the literature, the number of design alternatives that a team considers seems to have some bearing on how well the needs of the different specialty groups are satisfied. This question explicitly asked the interviewee to describe how many alternatives were considered and the manner in which they were developed and/or compared.

What factors or events were the most critical *to resolving the issue?*

This question was used as a final check to ensure that the notes already taken accurately reflected what the interviewee felt was important.

4.3.2. Outcome and Demographic Questions

Outcome data was collected using a series of subjective measures based on seven-point Likert scales. Similar scales were also used to collect demographic information for each case. When asking these questions, written copies of the scales were shown to the interviewees to clarify the scales' meanings (see Figure 4.1 for an example and Appendix A for all of the scales).

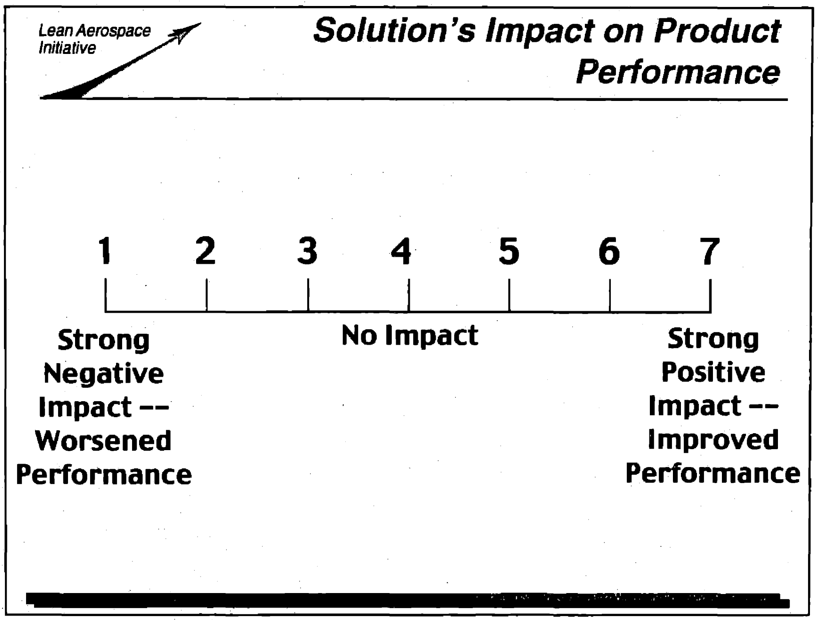


Figure 4.1: An example of the subjective rating scale used during interviews.

Subjective outcome measures were chosen for several reasons. First, because of the range of cases that would be studied (from product design to factory floor improvements), few specific quantitative metrics could be identified that would apply across all cases. Second, companies were often unwilling to release specific numerical data about product or project performance or cost due to competitive concerns. Finally, and perhaps more importantly, since paired interview data was to be collected, it was anticipated that outcome "performance" would be measured differently by individuals from different groups (e.g., "drag" for an aerodynamicist and "part count" for a manufacturing engineer). Consequently, subjective measures were selected to allow each interviewee to mentally tailor the specific measure to the metrics he or she considered most important.

For each question described below, the range of the Likert scale is given in parentheses after each question.

How satisfied were you with the final resolution to the problem? (1 = not at all satisfied; 7 = very satisfied)

This question allowed the interviewee to rate his or her overall level of satisfaction with the outcome to the problem.

Did the problem come up again, i.e., did it have to be "solved" repeatedly? (1 = yes, many times; 7 = no, never came up again).

This question was intended to gage how well the team solved the problem, by asking whether or not they had to solve it repeatedly – that is, whether or not the team believed that they had solved the problem only to discover a short time later that the problem still lingered. *This question was dropped from later analysis, however, because interviewees had difficulty interpreting the intent of the question.*

Please rate the solution's impact on the product's performance compared to original goals. (1 = strong negative impact, decreased performance; 4 = no impact; 7 = strong positive impact, improved performance)

This question allowed the interviewee to mentally select those performance metrics most important to him or her, and then rate the solution's performance relative to those measures, Furthermore, this subjective approach avoided the arbitrary selection of a metric that may or may not have been significant to the individual.

Please rate the solution's impact on the product's cost compared to original goals. (1 = strong negative impact, increased cost; 4 = no impact; 7 = strong positive impact, lowered cost)

Since cost is such an important factor in the defense industry today, this question was used to investigate any factors that may have a direct impact on cost.

Please rate the solution's impact on the project's schedule compared to original plans. (1 = strong negative impact, missed deadlines; 4 = no impact; 7 = strong positive impact, finished ahead of schedule)

Similar to the previous two questions, this one was intended to study factors that may have contributed to effects on a project's schedule.

Did the solution result in any downstream engineering changes to the product or to changes to associated systems or components? (1 = yes, many engineering changes, or a few large changes; 7 = no changes)

Engineering changes are often used as a measure of design team performance, so this question was intended to measure such changes. However, interviewees often had trouble judging these impacts, and in a significant number of cases were not certain enough to provide any answer. Consequently, *this question was omitted from any analyses.*

Please rate your previous experience with similar problems. (1 = have never seen a problem like this before; 7 = have solved similar problems many times in the past)

This question was intended to help control for any "familiarity" effect in the cases that were studied.

Please estimate the complexity of the problem, accounting for both technical and social factors. (1 = simple; 7 = complex)

This question was intended to investigate what effect, if any, the relative complexity of a problem had on the factors that were judged to be important in solving it.

Please rate your degree of prior experience working with the other members of the team. (1 = have never worked with the other members before; 7 = have worked with the other members many times in the past)

This question was intended to investigate what effect, if any, a person's familiarity with the other members of the team had on the factors that were cited as important to resolving the problem.

Please rate the accuracy of your memory of the situation. (1 = do not remember the case well; 7 = remember the case very well)

Used as a final check, this question helped to ensure that interviewee data could be treated as reliable. (Several cases were thrown out due to very low memory ratings by the interviewees.)

4.3.3. Quantifying Differences in Problem Interpretation

Two measures were developed in order to quantify differences in problem interpretation. The first was the "Ratio of Unique Criteria to Total Criteria Cited", or "unique criteria ratio". This measure was used only for paired cases, and was the ratio of unique criteria cited by each interviewee of a pair to the total number of criteria cited across both interviewees. For example, suppose the first interviewee cited *weight*, *cost*, *number of new manufacturing processes*, *number of assembly steps,* and *manufacturability* as her criteria, while the second interviewee cited *performance*, *cost*, *weight*, and *payload capacity*. The total number of criteria cited across the pair would then be nine. Since both cited *cost* and *weight*, those two criteria are not unique. The criteria *number of new manufacturing processes*, *number of assembly steps*, *manufacturability*, *performance*, and *payload capacity*, on the other hand, were each only cited by one of the two interviewees. Therefore, those criteria are considered "unique" and the ratio would be 0.56 (five unique criteria divided by nine total criteria).

The second measure used to quantify differences in problem interpretation was the "Ratio of Unique Problems to Total Number of Problems", or "unique problem ratio". Again used only for paired interview cases, this measure compared the problems that each member of a pair were solving. As will be discussed, engineers tended not only to describe problems using different criteria, in several cases they also described different *problems*. Consider again the lists of criteria given above. These lists essentially describe two problems. The first problem, described by both hypothetical interviewees, relates to product performance. This problem is characterized by the criteria *weight*, *cost*, *number of parts, performance*, and *payload capacity* – all of these criteria describe aspects of the product itself. The second problem, however, relates to the manufacturing process that will be used to produce the product. This problem is described by the criteria *number of new manufacturing processes* and *number of assembly steps*. While interrelated, these two problems a physically different. Therefore, the unique problem ratio would be $^1/_2$ or 0.5 – there are two total problems, the manufacturing-related one and the product-related one, and the manufacturing-related problem was considered by only one interviewee.

4.4. Operationalized Hypotheses

The measures defined above can now be used to operationalize the generalized hypotheses presented earlier. These refined hypotheses are:

Hypothesis 1: Engineers from different specialties will describe the same design problem using different criteria.

Hypothesis 2: Engineers whose criteria lists are more similar -- whose lists have unique criteria ratios and unique problem ratios closer to zero -- will solve problems more effectively, as measured in terms of satisfaction and product performance, product cost, and project schedule impact.

Hypothesis 3: Cases in which design problems are solved using tools that illustrate constraints and requirements will result in higher satisfaction and product performance, product cost, and project schedule impact scores than cases in which tools that illustrate solutions are used.

5. RESULTS

This chapter will present the key findings of this investigation. An overview of the scope of the data collection effort will first be presented, followed by a description of the data analysis process and examples of key factors. Finally, key results related to each hypothesis will be presented.

5.1. Data Collection Scope and Analysis Process

Data was collected during visits to corporate members of the Lean Aerospace Initiative (LAI) consortium. These companies provide financial support for LAI, along with guidance and data collection opportunities. Interviews were conducted at each site during one to four day visits. Interviews lasted from thirty minutes to just over an hour. Depending on their time and willingness to participate, each interviewee provided one to two cases. When possible, each interviewee was asked to provide an example of an "easy" case and a "difficult" case, as previously described. Due to individual experiences, however, study participants did not necessarily have one example of each. Consequently, the final data set does not include an even number of easy and difficult cases.

Overall, ninety-six interviews were conducted for this research. Of this total, seventy interviews were "first" interviews – the initial interview used to identify a paired case. These interviews resulted in a total of 98 cases (using just one individual's perspective). Thirty-three cases were classified as "easy" by the interviewees, thirty-eight as "difficult" and twenty-seven were unclassified in terms of degree of difficulty. For analysis purposes, unclassified cases were grouped with the difficult cases. Twenty-six interviews were "follow-up" interviews, yielding twenty-six cases for which two perspectives were obtained. Cases were further divided in two primary ways: first, based on the major parties involved in the problem and, second, based on the development phase during which the problem occurred. Table 5.1 and Table 5.2 summarize these statistics.

Table 5.1: Number of individual-interview cases by "Dispute between" and "Phase".

		Dispute between...						
		Across Groups			Across Firms			
		Factions within a Specialty Group	**Engineering and Another Engineering**	**Engineering and Manufacturing**	**Manufacturing/Industrial Engineering and Line Operators**	**Engineering and a Supplier/Customer**	**Manufacturing/Industrial Engineering and a Supplier/Customer**	***Total (by Phase)***
Phase during which Dispute Occurred	Conceptual Design	2	4	0	0	7	0	13
	Preliminary Design	2	1	1	0	0	0	4
	Detail Design	2	4	1	0	4	0	11
	Product Improvement, EMD, or Prototype Testing	9	7	8	2	5	0	31
	Mass Production	1	2	10	13	1	2	29
	Total (by Group)	16	18	20	15	17	2	

Note: Dispute between or Phase not indicated for 10 cases.

Table 5.2: Number of paired-interview cases by "Dispute between" and "Phase".

		Dispute between...						
		Across Groups				Across Firms		
		Factions within a Specialty Group	Engineering and Another Engineering	Engineering and Manufacturing	Manufacturing/Industrial Engineering and Line Operators	Engineering and a Supplier/Customer	Manufacturing/Industrial Engineering and a Supplier/Customer	*Total (by Phase)*
Phase during which Dispute Occurred	Conceptual Design	2	1	0	0	1	0	4
	Preliminary Design	1	0	0	0	0	0	1
	Detail Design	0	1	0	0	1	0	2
	Product Improvement, EMD, or Prototype Testing	2	4	0	0	1	0	7
	Mass Production	0	1	6	0	0	0	7
	Total (by Group)	5	7	6	0	3	0	

Note: Dispute between or Phase not indicated for 5 cases.

5.2. *Analysis Process: Identification of Facilitating and Hindering Factors*

In order to provide a framework to analyze the interview data, a list of factors that interviewees cited as facilitating or hindering problem solving processes was generated. This list was revised several times over the course of the study, both to better capture the intent of the interviewees' descriptions and in an attempt to generate a statistically significant and stable dataset. For each case, a factor was "scored" as a "1" if the interviewee cited it as important and "0" if it was not cited. It should be noted that score of "0" did not necessarily mean that a factor was totally absent from case – it simply indicates that the interviewee did not specifically signify that the factor was important. For example, "co-location" is one of the factors cited in several cases. However, in several instances, team members were co-located, but interviewees did not indicate that co-location played an important role in solving the problems. In such instances, co-location was scored as a "0". Furthermore, multiple factors may have been scored "1" for any one case. Thus, if an interviewee noted the importance of both co-location and the use of a trade study, both factors were scored as "1".

The factors were divided into two broad categories: factors that facilitated resolution of a problem and factors that inhibited resolution. The following two sections detail each factor, along with examples from interview data. Appendix B shows all of the factor data.

5.2.1. Factors Facilitating Problem Resolution

Management Intervention

Definition: In order to solve the problem, management was asked to step in and make a final decision for the team, or, because the team was unable to do so on its own, management intervened without the team's request to settle a dispute.

The design of a weapon system's power subsystem provides an example of management intervention. Early in the subsystem's development, a relatively new architecture was chosen for the design. As the program evolved, however, a change to a related subsystem caused the power subsystem engineering group to re-evaluate its initial decision. The group conducted a series of computer simulations of alternative architectures and ultimately decided to change the system to a more "traditional" configuration. These results were then presented to other specialty groups working to develop the weapon system, several of whom were opposed to making the change (due to its impacts to their elements of the system). As a result of the developing impasse, the issue was raised to the level of the program's chief technologist (a senior manager). The manager reviewed the power group's simulations and requested an additional series of tests and evaluations. After these requests had been satisfied, the manager mandated that the power subsystem group's change be implemented, forcing the other groups to accept the modification.

Critical Team Member

Definition: A single member of the team was crucial to settling a dispute, either by "doing the leg work", serving as a negotiator or mediator between groups, or developing a key technical insight.

An example of a critical team member is demonstrated by the design of a tool to repair fatigue cracks found in an aircraft's fuel tank. The engineering group at the company responsible for fixing the cracks had determined that a portion of the tank would have to be cut out and a metal "patch" installed. The challenge to the tooling group, therefore, was to design a cutting tool that would fit into the narrow space of the fuel tank. Initially, the tooling engineering lead did not believe it would be feasible to develop a tool with the needed capabilities. After some initial design work, he was directed to contact another tool designer at one of the company's other sites. Communicating via phone and fax, the other designer was able to conceive of a tool that met the group's needs. Thus, the tool designer served as a "critical team member" – without his input, the tool itself might not have been developed.

Reliance on Engineering Expertise

Definition: The problem's solution was a result of "good engineering", careful thought and reflection, or creativity.

An engineering team at a automotive manufacturer was confronted with a problem when styling changes displaced a taillight on a new version of a car design. In particular, the challenge was how to package the light and its electronics given the new constraints imposed by the styling choices that had been made. As one of the engineers involved in designing the installation for the light described, the solution was the result of "lots of thinking in the car." In this case, no specific design tools (such as computer aided design packages or rapid prototypes) were used – the engineers simply spent time considering the problem in their minds. Such a process was therefore characterized as "reliance on engineering expertise".

Use of Trade Studies

Definition: The team conducted a trade study (formal consideration of multiple options which are compared against an explicit set of metrics), and the development and execution of the study was critical to solving the problem.

The process used by an aircraft design team to select the configuration for an aircraft's control surfaces provides a classic example of a trade study. The team consisted of engineers from multiple sites within the company, and the engineers from each site had different "philosophies" regarding the benefits of various configurations. In order to create a consensus on which approach to follow, the team developed an extensive trade study to select a configuration. The first step in the study was to agree to a set of engineering metrics that would be used to judge the benefits and drawbacks of each design alternative (for example, weight and performance). In addition, the engineers agreed to a series of qualitative methods of comparison, to add to their understanding of the merits of each design (for example, marketing considerations). The team then developed a range of configuration alternatives. These alternatives were compared using the previously agreed to metrics. Based on a combination of the qualitative and quantitative metrics, the team was able to reach a consensus on which configuration to pursue.

Show and tell

Definition: Showing a boundary object (such as a model of the product, a drawing, etc.) was critical in helping the group solve the problem.

As discussed in Section 4.1.2, a boundary object is a physical object that helps to communicate a design problem or show relationships in a problem. In this instance, "show and tell" has a specific meaning that must be clarified. An example helps to demonstrate this factor's meaning.

An aircraft subsystem design team faced a problem with the airflow from a cockpit windshield defog nozzle. The nozzle was not providing the proper defogging performance, and this problem was traced to a stagnation point in the nozzle's airflow. Uncertain of the specific cause of the problem, the manager responsible for the nozzle needed to bring together his entire multidisciplinary team to address the issue. The team included individuals that would be critical to solving the problem who had little to no knowledge of nozzle aerodynamics, such as the manufacturing engineers.

In order to illustrate the stagnation point, the manager and some of his aerodynamicists built several models they could use to illustrate the problem. First, the actual nozzle was mounted to the end of leaf-blower – it turned out the leaf blower's mass flow rate was similar to the flow rate of the installed nozzle. Tufts of thread were then taped to the nozzle. When the leaf-blower was turned on, the tufts of thread in the stagnation area would stay limp while the others would blow straight. This phenomenon was video taped, and the tape was then shown to the other team members to explain the problem during a meeting. To further help the other engineers appreciate the issues, the nozzle was also attached to a hair dryer that was brought to the meeting and passed around, allowing everyone to experiment with the nozzle on his or her own.

Use of Tests

Definition: The use of tests and test data (whether real or "virtual"/computer simulated testing) was critical in helping the group solve the problem.

The use of tests is distinguished from showing boundary objects and trade studies on the basis of process and intent. A trade study is characterized by its comparison of multiple design options, and show and tell is distinguished by one group creating an object that is then shown to another. A test, in contrast, is typically done "to prove" a hypothesis, i.e., a test is part of an experiment that includes a hypothesis to be proven or refuted.

For example, the area around several rivets on an aircraft skin suddenly began to develop "dimples" during production. A multidisciplinary team, including engineers and factory line operators, was formed to resolve the problem. Initially, many of the team members believed they "knew" the source of the problem. Such assertions, however, simply led to heated debates.

One of the engineers on the team then grew suspicious of the operating settings that had been programmed into the riveting tool. The engineer went to a similar tool on another aircraft's assembly line. Bringing the factory machine operators with him, he first checked the machine's operation using the nominal operating parameters for the problematic machine. These settings produced the correct results. He then entered the actual parameter values that were being used on the problematic machine. These settings recreated the dimpling problem, thus demonstrating that the dimpling problem lay specifically in the settings being used on the machine. Thus, the important elements of "use of tests" were clearly illustrated: the hypothesis, followed by a test to prove or disprove the hypothesis.

It is important to note that two key features distinguished "use of tests" from "show and tell": participation and context. As described above, "show and tell" was typified by instances in which one member (or subgroup) of team brought an artifact (such as a boundary object) to a team meeting and then pointed to that object during a discussion. "Use of tests," on the other hand, required that the team as a whole either agree to conduct the test or that the team as a whole in some way witnessed the test itself. That is, "use of tests" was a more inclusive event.

Furthermore, "use of tests" maintained a greater amount of a problem's context than did "show and tell." For instance, in the nozzle example described above, a leaf-blower substituted for the actual nozzle arrangement. While this demonstration illustrated the stagnation points on the nozzle, it could not be used to show the interaction between the nozzle and cockpit or the rest of defog system. In contrast, in the testing example just discussed, the engineer demonstrated the problem on the factory floor using actual factory machines, thereby retaining more of the problem's original context.

Time Pressure

<u>Definition</u>: The team was under significant time pressure, and this pressure helped the team to reach a consensus.

An example of time pressure was provided by a product improvement initiative for an aircraft. Several structural beams on the airframe tended to be damaged during assembly, resulting in expensive rework. A multidisciplinary design team was assembled to solve the problem. The team began to flounder from a variety of social and technical challenges. Finally, upper level management established a firm deadline by which the project had to be completed. The establishment of this specific date provided the pressure the team needed to focus on the problem and make the necessary compromises to create a consensus regarding a solution.

Co-located Team

Definition: All team members were physically located in close proximity, and this proximity was helpful in solving the problem.

During early tests of a new aircraft, problems were uncovered with a fuel sensor. Different elements of the total fuel system, however, were controlled by different groups within the company, and these groups were geographically dispersed. In order to solve the problem, the engineers with the needed expertise were all temporarily relocated to a common work area. The ease of communication facilitated by this common area was an essential element to helping the group quickly solve the problem.

Frequent Face-to-Face Meetings

Definition: Although not co-located, the team met regularly to review their progress and discuss the problem.

For example, a new car design team was having trouble designing an interior console unit. Specifically, the problem centered on how an access door on the console should operate. The design favored by engineering was disliked by styling. The engineers, stylists, and their managers held meetings on a regular basis, at which engineering and styling would present their latest design concepts and critique each other's ideas. Over the course of these meetings the team developed a mutually suitable design that was ultimately selected for production.

Shared Objectives or Well Understood Requirements

Definition: All members of the team evaluated the design or were themselves evaluated on the basis of a shared understanding of the team's purpose or on shared performance measures.

A good illustration of the power of shared objectives or well understood requirements is shown by a design team's decision to move a production break in the manufacture of a new aircraft. The plane was to be built by several companies, each company responsible for a different section of the vehicle. An initial series of decisions were made during conceptual design about the location of these production breaks and the workshare the breaks represented. As the design's detail increased, however, the engineers came to realize that using the original break in one location would make the aircraft difficult and costly to produce. The team began to debate how the break should be moved, a debate with significant consequences: Moving a production break could change the amount of money the companies would earn. However, two factors were particularly important to the team because of their importance to their customer: weight (which affected the product's performance) and schedule (when the customer would receive the aircraft). A comparison of the different options for moving the production break showed that a shift in the break would have significant benefits for these two measures. Consequently, even though one of the companies would lose some its workshare, the engineers from that company agreed to the shift.

Development of a Win-Win Solution

Definition: The problem was resolved because the team developed a solution that improved the design's performance along multiple dimensions.

For example, during the development of a technology demonstration version of a new weapon system, one of the subsystem engineering groups developed a novel approach for using a back-up power generator to provide supplementary power during the weapon system's normal operation. This idea was developed to solve several problems the group was facing. The concept, though unconventional, also had benefits for other subsystem groups, such as reducing the weapon system's weight, leading to improved performance, and allowing for the elimination of some other components, reducing the cost of the demonstrator. While the subsystem group originally proposed the change because of the advantages it offered relative to their own measures of performance, these additional benefits meant that other groups had reasons to support the change as well.

Delineation of Technical Issues/"Reasons Why"

Definition: Special efforts were made to explain the technical aspects of a problem to individuals from other groups rather allowing team members to argue over opinions.

The debate over the approach used to install a structural upgrade to an airframe illustrates this factor. Initially, the manufacturing representatives on the team developing the upgrade proposed an installation scheme. The design engineers did not support the proposed approach, and in the ensuing debate, the group appealed to their manager to resolve the problem. The manager refused to force a decision, however, and sent the team back to settle the issue on its own. Ultimately, the design engineers used what one of them referred to as a "logic argument":

the designers slowly and meticulously explained to the manufacturing engineers why their proposed approach would not work and why an alternative approach would. Eventually, based on this reasoned argument, the manufacturing engineers agreed to the alternative method.

5.2.2. Factors Inhibiting the Resolution of a Problem

Social Problems

Definition: The presence of negative social factors, such as lack of experience working together, "cultural" differences, or historic mistrust, inhibited the team's ability to resolve the problem.

A "classic" example of this problem was illustrated by a manufacturing engineer describing a case about producibility problems with an aircraft part. The part in question, a complex composite component of an aircraft body panel, could not be reliably produced based on its original design. The manufacturing engineers responsible for the part then approached the design engineers to request a change to the design. Historically, however, the company's different groups had interacted using an "over-the-wall" model: design would develop a part concept and then pass it on to manufacturing, who would then produce the part, without providing any feedback to design. In this case, however, extensive changes were required to the part if it was to be produced reliably. The lack of past interactions, however, initially hindered the ability of the manufacturing and design groups to work together to develop a solution.

Misuse of Boundary Objects or Test Data

Definition: Boundary objects or test data were used by one side of a dispute in a fashion that misconstrued the truth or the important relationships of a problem.

Again, a case of manufacturing-to-engineering interaction provides an example of this factor. Similar to the case described above, a new aircraft component made of composite materials could not be reliably produced. Manufacturing engineers brought this problem to the attention of the design engineers in order to address the problem. When first presented with the issue, the design engineers noted that a pilot program had been run demonstrating the manufacturing techniques used to produce the composite component. The results from that pilot program, the designers noted, suggested that the manufacturing process was adequate, and, therefore, no change to the part's design was necessary. This conclusion, however, was faulty. While the pilot program had been considered a success, the tests had been conducted on parts with relatively simple shapes. The production part, in contrast, had a complex shape, and the manufacturing problems were directly related to the production of these complicated features. The results of the pilot program, consequently, were not a reliable representation of the problems that were being confronted in the production of the final part. Therefore, the designers were misusing the results of the pilot program.

Poorly Defined or Understood Requirements or Lack of Shared Metrics or Objectives

Definition: Different members of the team interpreted the team's requirements or performance metrics differently, making problem solving difficult. Or, the lack of shared metrics inhibited the team from reaching a consensus.

A debate over the installation of a tow hook in a new car design demonstrates this factor. During the development of an export version of a new car, a debate arose over where a tow hook should be built into the vehicle. The engineers were basing their arguments on a company guideline for export market tow hook design. Using this guideline, however, resulted in a design of which styling did not approve. The debate continued in circles for several weeks. One of the engineers assigned to the issue then began to study the guideline itself. He discovered that the company guideline was based on an amalgam of requirements from several different segments of the export market. Consequently, there was no one specific tow hook installation requirement – the guideline essentially represented an "average". The engineers pushing for the design to conform exactly to the guideline did not know this, however, and this lack of understanding fueled the debate. Once the requirement was clarified, a final design decision was made, though several of the design engineers remained displeased with the final result (because of their interpretation of the design guideline).

Unclear or Split Lines of Communication and/or Authority

Definition: Team members did not know for certain who was in charge, or the team debated who was in charge. Or, communication channels between team members were indirect, requiring multiple handoffs or intermediaries.

A case related to manufacturing quality illustrated both aspects of this factor. An aircraft component supplier's engineering group was not satisfied with the quality of a weld on a component during production. In an attempt to correct the problem, the engineering group began investigating an alternative welding method. The engineers asked for and initially received support from the tooling group to help develop the new welding method and the requisite tools. Once some initial work had been completed on the new approach, the engineering group wanted to test it on the production line. The line, however, was located overseas and was in the midst of full rate production. Consequently, the plant manager was unwilling to shut down the line to allow engineering to experiment with the new tool. At that point, it was unclear who had more authority – the engineers or the plant manager. Development of the tool (and, therefore, the elimination of the welding problems) slowed until the groups could determine who had decision making authority for running the tests.

5.2.3. Consideration of Alternatives

The final factor that was recorded was the manner in which the team considered design alternatives. Three possible approaches were identified: (1) serial or iterative development of one idea at a time; (2) parallel consideration of two design options; and (3) parallel consideration of three or more design options. Interviewees were specifically asked to indicate what approach was used for each case they described. Note, however, that a response of “2” or “3” (parallel consideration of two or three or more alternatives) did not necessarily mean that an interviewee cited trade studies as important. In several cases, for instance, interviewees said that they did consider two options in parallel, but that no formal trade study was done to select between them – the decision was based on less formal processes and judgements.

5.3. Hypothesis One: Implications from the Data

It will be recalled that hypothesis one stated that engineers from different specialties interpret design problems differently and that these differences could be measured using the unique criteria ratio and unique problem ratio. Table 5.3 shows the mean, high, and low scores for these two measures. Several important points can be taken from this simple table. First, on average, each member of a pair listed a different set of criteria than did his or her counterpart (i.e., the mean value of the unique criteria ratio was not zero). This result suggests that engineers from different specialties *do interpret the same problem differently*. Returning to Korzybski's model of abstraction, one could say that one engineer abstracts a different set of criteria from a design problem than does another. Perhaps more importantly, this result demonstrates that engineers *evaluate* design problems differently, a topic to be addressed in greater detail below.

Table 5.3: Mean, high, and low results for the unique criteria and problem ratios.

	Mean	**Low**	**High**
Unique Criteria Ratio	**0.56**	**0.2**	**1**
Unique Problem Ratio	**0.32**	**0**	**1**

Notes:
Total number of cases for which data was available = 18.
For both ratios, a 1 indicated completely different responses by each interviewee in a pair, while a zero indicates exactly the same response.

Table 5.3 also indicates that, on average, the two members of each interviewed pair actually were considering *different* problems (i.e., the mean value of the unique problem ratio was nonzero). That is, a given design problem does not consist of a single issue, but consists of a *set* of interrelated problems, the nature of which can vary to a great degree. Examples help to illustrate both differences in problem definition and differences in criteria.

5.3.1. Case Examples

Consider first a case in which both interviewees in a pair were addressing the same problem (unique problem ratio was zero) but they each considered a somewhat different set of criteria. An example of such case revolved around the design and development of a customized manufacturing tool for a large aerospace component (case 82 in Appendix C). The tool was designed to move along a part and to drill holes perpendicular to the surface along the part's length. The criteria lists for the two engineers interviewed from the project are shown in Figure 5.1 (note that in this case, both interviewees were design engineers). Arrows between criteria in the figure indicate shared criteria, and since there are seven total criteria, three of which are unique, the unique criteria ratio was 0.43 (three divided by seven). All of the criteria address the same problem, the design of the tool. Therefore the total number of problems was one, and since there are no unique problems, the unique problem ratio was 0.

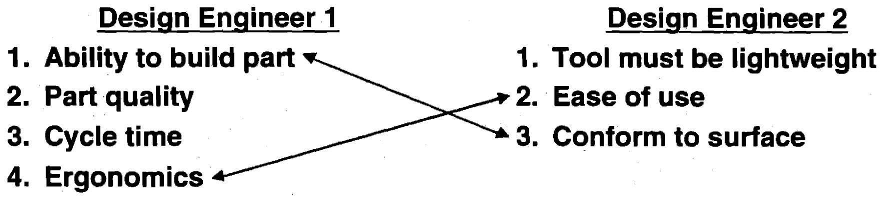


Figure 5.1: Comparison of problem definitions: shared problem, but different criteria (arrows indicate shared criteria)[2].

Therefore, although both designers were concerned about the design of the tool and its performance, they were evaluating its performance slightly differently. Both wanted to ensure that the tool be easy to use and that it conform to the contoured surfaces on which it was intended to operate. However, design engineer 1 seemed to be more concerned about the manufacturing performance of the tool, as indicated by the criteria *part quality* and *cycle time.* Note that both of these criteria are still related to the design of the tool – they are a measure of tool performance – so engineer 1 is not addressing a different problem than engineer 2. The

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[2] Throughout this work, criteria are listed in the order in which they were stated by interviewees – no particular significance should be attributed to their ordering. In most cases, criteria are listed as direct quotes from interviewees. However, in order to ensure confidentiality and protect proprietary data, terminology has been altered in some instances.

differences in criteria, however, do indicate that the engineers are *evaluating* the design somewhat differently.

Other cases, in contrast, demonstrate that engineers are often solving different problems. For example, the case of a manufacturing problem with a large, machined aircraft component (case 68 in Appendix C) illustrates how the range of issues considered by engineers can vary. The problem itself centered on the inability of a manufacturing process to meet the tolerance requirements for holes that were reamed into the part. One interview was conducted with a manufacturing process engineer and the other with a design engineer. The criteria given by each interviewee are reproduced in Figure 5.2.

Process Engineer	**Design Engineer**
1. Meet part acceptance criteria	**1. Do not invalidate data from fatigue test article**
	2. Ensure that worst case manufactured part still meets acceptance criteria
	3. Do not impact aircraft aerodynamics
	4. Do not affect part interchangeability

Figure 5.2: Illustration of different criteria and different problems (arrow indicates shared criteria).

The most obvious contrast between the lists in Figure 5.2 is the difference in the number of criteria: the process engineer listed only one while the design engineer listed four. For the process engineer, the problem revolved around the manufacture of the part itself. Therefore, the criterion that most mattered to him was that the part meet its acceptance criteria. Once the part met these criteria, the problem would be solved. The design engineer, in contrast, was concerned about several additional factors. First, a fatigue test aircraft had already completed several rounds of testing to certify the airframe's fatigue life. The design engineer wanted to ensure that any changes made to correct the holes would not invalidate the previously collected fatigue testing data and consequently require a new round of testing (which was expensive and time consuming). In addition, the design engineer desired that any changes made to the part not impact the aircraft's aerodynamics which could potentially decrease the aircraft's performance. Finally, he also wanted to ensure that the part remain interchangeable, i.e., that a part from one plane would be able to fit without difficulty onto another plane.

These differences in criteria translate into different problems. The first problem, shared by both engineers, was to solve the part quality dilemma (represented by the criteria *meeting acceptance criteria* and *ensure that worst case manufactured part still meets acceptance criteria*). The design engineer, however, was also concerned about three other problems: maintaining the validity of the fatigue test data, avoiding degradation to the aircraft's aerodynamic performance, and ensuring that the parts remained interchangeable. Thus, while they were both solving one problem, the design engineer was also worrying about several others.

Another example illustrates that differences in problem definitions may be the result of a solution to one problem creating a new problem. Figure 5.3 illustrates the criteria lists from a tool designer and an engineer involved in a fatigue crack repair for an in-service aircraft (case 103 in Appendix C).

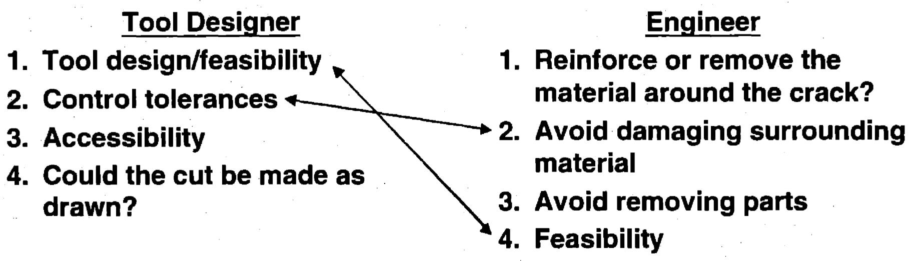


Figure 5.3: Criteria lists illustrating how solutions created by one engineer generate problems for another (arrows indicate shared criteria).

As can be seen, the two engineers shared several concerns and also had some worries unique to their realms of expertise. From the engineer's perspective, the first issue was deciding how to repair the crack – whether the cracked material should be reinforced or removed from the structure. The details of this decision were outside of the tool designer's expertise, and, consequently, were not issues about which he worried. Once the engineer made the decision to remove the material, the engineer and the tool designer confronted a shared problem: could it be done? Thus, both interviewees cited concerns regarding the feasibility of removing the material and both were concerned about the potential of damaging nearby structure. The tool designer, however, also had to address problems about which the engineer was not concerned: specifically, issues related directly to the human reality of making the repair. For example, while the engineer could readily illustrate on drawings what region of material needed to be removed, the ability of a human being to access the area, insert a tool, and then make the cut was less clear. Issues such as this one were of primary concern for the tool designer, while the engineer hardly even mentioned them during the interview. For the engineer, the problem was framed in terms of the crack's impact on the aircraft's structure; for the tool designer, the problem was framed in terms of a human reaching the crack. Therefore, in this case, one engineer's solution created a set of new, *physically different* problems for another engineer.

5.3.2. Discussion

The above examples help to highlight several important issues. First, the criteria lists formally illustrate that engineers from different specialties do interpret design problems differently. In fact, in many instances, engineers from *within the same specialty* had slightly different interpretations of the same design problems. Thus, the first hypothesis has been confirmed.

The collection of the criteria lists also helps to illustrate a further point: engineers may *evaluate* a solution to a design problem differently. This result reinforces some of the theoretical arguments put forward in section 3.2.6, namely, that what one knows includes both how to do something and how do it correctly. As this study has shown, in the case of engineering design problems, engineers from different groups are likely to use different evaluation systems (as evidenced by different criteria) to judge the suitability and desirability of a given solution to a problem.

That the differences between specialists lies in their evaluation systems is significant and has important practical consequences. Design disputes can often take on a character of "right" versus "wrong", one group arguing that the solution put forward by another group is wrong while theirs is right. Differences in evaluation systems, however, mean that the issue is more complicated. According to one side's *evaluation method*, one alternative may appear better than another, while the reverse conclusion may be reached by the other side using a different evaluation method. But, in "reality", one alternative is not intrinsically better than another. Rather, the criteria used to evaluate the alternatives define and limit the ways in which the alternatives can be *interpreted* as having benefits or drawbacks – "goodness" and "badness" are abstractions of the alternatives, not characteristics of the alternatives themselves. Consequently, an important step in the design problem solving process would appear to be the harmonization of evaluation systems, or the development of a shared means of judging the suitability of a design. This issue will be addressed in greater detail below.

The criteria lists also help to demonstrate that multidisciplinary problem solving is complicated along another dimension: specialists may in fact be solving different problems. As the examples above illustrated, engineering design problems often consist of multiple "layers" of problems. Marples (1961), during his studies of the design of nuclear reactors, made a similar observation. He suggested that the engineering design process progressed through a hierarchy of problem identification and problem solution. Engineers would be confronted with an initial problem, and the solution to that problem would in turn create a new set of subproblems. Thus, in the fatigue crack repair example discussed above, the initial problem was deciding how to repair the crack (reinforce or remove), and the subsequent subproblem was the design of the tool that would remove the damaged material. Similarly, in the manufacturing problem (case 68), the initial issue was the inability to meet part tolerance requirements, and its subproblems were the potential impacts to the fatigue test data, aerodynamic performance, and part interchangeability.

Furthermore, this research suggests that not only do solutions to problems create their own set of new subproblems, but that the responsibility for solving the problems shifts. Thus, the engineer was responsible for determining how to repair the fatigue cracks, while the tool designer was responsible for determining how to implement the repair. As with the criteria lists, this phenomenon has important consequences. Specifically, a design dispute may not only be the result of different evaluation systems, it may be the result of different evaluation systems being applied to *different problems* – the solution to one engineering group's problem is likely to become the next problem for another group. Thus, resolving cross-functional disputes requires a process that captures not only differences in evaluation methods, but also that demonstrates how solutions and their attendant subproblems are linked. Such processes will be addressed in the coming sections.

5.4. Hypothesis Two: Implications from the Data

The second hypothesis for this research suggested that cases with unique criteria and unique problem ratios closer to zero would result in higher satisfaction and performance, cost, and schedule impact scores than cases with ratios closer to one. In other words, it was expected that when engineers had more similar definitions of a problem, they would be able to solve that problem more effectively.

Unfortunately, the data do not provide any conclusive relationships between these measures. No correlations could be identified between the "input" measures, the unique problem ratio or the unique criteria ratio, and the "output" measures, satisfaction or performance, cost, or schedule impact. Therefore, the hypothesis cannot be accepted, nor can it be rejected – the data provide no clear indication in either direction.

There are several possible explanations for this ambiguous result. First, the sample size is relatively small – criteria lists could be collected for only nineteen paired cases. With additional cases, more definitive relationships may have been revealed. Moreover, the outcome measures may not be sufficiently sensitive to distinguish any differences. This possibility is supported by other research. Wanous et al, 1994, for example, specifically investigated the relationships between problem solving *process* performance indicators and *outcome* indicators and noted that few strong correlations could be identified. Perhaps if less subjective, more quantitative measures had been used in this study, differences between cases with low and high unique criteria and problem ratios could have been identified.

Furthermore, the nature of the design problems studied for this investigation complicated performance measurement. All of the problems that were studied had to be solved. If the teams did not solve the problems in some way or another, their development projects would have ground to a halt. Therefore, ultimately all of the problems were resolved. Again, the result of this trend is that the outcome measures appear to not be sensitive enough to indicate many differences between cases.

Another possible explanation for the ambiguous outcome is that the question used to study the relationship between problem definition and problem solving performance was incorrect. To address this hypothesis, each interviewee was asked to provide a list of criteria that were important to him or her in judging a potential solution. The nature of the question, therefore, was personal – it asked the interviewee to only cite factors that were important to him- or herself. Problem solving performance, however, may not depend solely on such a personalized definition. Instead, an individual may consider two sets of criteria during problem solving – those important to himself and those that he believes are important to the other members of his team. Based on the criteria he believes to be important to the other individuals, the individual may "temper" his threshold for a given criterion.

For example, in the fatigue crack repair example described above, the tool designer commented that human access to the repair site, though possible, was still difficult. Therefore, he was not completely happy with the final outcome, but he understood that given the constraints faced by the group and the need to make the repair, the decisions that were made were the best ones possible. In a sense, then, he lowered his standards for accessibility in order to facilitate solving the problem.

Clearly, additional work is required to better understand these issues. Specifically, future investigations should consider collecting data on what criteria an individual believes are important to *other* members of the team, in addition to the criteria the individual considers to be important to himself. Furthermore, interviewees should also be asked how the criteria that are important to other members of the team affect the extent to which they will argue in favor or against an alternative based on one of their own criteria.

Despite the lack of clarity offered by these measures, another avenue of investigating this hypothesis exists. As described previously, one of the factors cited that helped to facilitate problem resolution was *shared objectives or well understood requirements*. The implications of this factor, relative to hypothesis two, will be addressed in the following section.

5.5. Hypothesis Three – Implications from the Data

The final hypothesis guiding this research argued that cases in which design problems were solved using tools that illustrated constraints and requirements would result in higher satisfaction and product performance, product cost, and project schedule impact scores than cases in which tools that illustrate solutions were used. This hypothesis will be addressed first through several statistical comparisons and then through case examples.

5.5.1. Statistical Analysis of the Data for Hypothesis Three

Four different numerical analyses were used to ascertain the importance and effects of the various factors that interviewees identified as facilitating problem solving. First, the frequency with which interviewees cited different factors was assessed, providing an indication of what factors the interviewees considered to be important. Then, a combination of correlations, regressions, and Mann-Whitney tests were used to judge the actual effects of these factors. Each test is discussed in turn.

Citation Frequencies

In order to determine what factors the interviewees considered most important in facilitating problem resolution, the frequencies with which they cited the various factors were compared. First, consider the citation frequencies in paired interview cases. These frequencies are shown in Table 5.4. Three values were compared: the frequency with which *one* member of the pair cited a factor as important, the frequency with which *both* members cited a factor as important, and the ratio between the number of times a factor was cited by both members of a pair to the total number of times the factor was cited.

Table 5.4: Paired interview cases: Citation frequencies of factors facilitating problem resolution.

Factor	N Cited by One (%)	N Cited by Both (%)	When Cited, % by Both
Use of Tests	2 (8%)	16 (62%)	16/18 (89%)
Show and Tell	7 (27%)	11 (42%)	11/18 (61%)
Frequent Face-to-Face Mtgs	11 (42%)	5 (19%)	5/16 (31%)
Shared Objectives/Requirements	5 (19%)	5 (19%)	5/10 (50%)
Use of Trade Studies	1 (4%)	4 (15%)	4/5 (80%)
Time Pressure	2 (8%)	3 (12%)	3/5 (60%)
Critical Team Member	4 (15%)	3 (12%)	3/7 (43%)
Co-location	4 (15%)	0	0/4 (0%)
Engineering Expertise	2 (8%)	0	0/2 (0%)
Management Intervention	6 (23%)	0	0/6 (0%)
Delineation of Tech Iss/Reas Why	2 (8%)	0	0/2 (0%)
Development of Win-Win Sol'ns	0	0	0

Notes
N Cited by One: Number of times a factor was cited by one member of the pair.
Percentage is relative to total number of cases (26).
N Cited by Both: Number of times a factor was cited by both members of the pair.
Percentage is relative to total number of cases (26).
When Cited, % by Both: Percentage of times a factor was cited by both members of pair, relative to total number of times it was cited by one or both members.

The table lists the factors in rank order based on the number of times a factor was cited by both members of a pair. As can be seen, the *use of tests* was cited most often, followed by *show and tell.* Subsequent factors had relatively small N's, for example, only in five of the twenty-six cases did both members of a pair cite *frequent face-to-face meetings* as important.

The significance of the factors to interviewees was further tested by taking the ratio between the number of times both members of a pair cited a factor as important and the total number of times the factor was cited (by one or both members of a pair). Using this comparison, *the use of tests* continues to be important: in sixteen of the eighteen cases in which it was cited, or eighty-nine percent of the time, *the use of tests* was cited by both members of a pair. This result suggests that when tests are used, their impact is considered important by both members of the pair, further indicating that tests are a useful tool in resolving design disputes.

The paired citation ratio for *trade studies* was also high, eighty-percent, but this is based on only five cases. Thus, while trade studies would appear to be a useful method for resolving design problems, the relatively small number of cases in which they were used prevents the development of a strong conclusion.

Show and tell, *shared objectives*, and *time pressure* all had paired citation ratios of about sixty-percent. Thus, these factors, when present, were important to both members of interview pairs, suggesting that they also play important roles in facilitating problem solving.

Citation frequencies for individual interview cases, both easy and difficult, are shown in Table 5.5. Again, these frequencies provide an indication of what factors interviewees tended to believe were important in resolving design problems. As was the case for the paired interview data, *the use of tests* and *show and tell* were the most frequently cited factors. Other factors cited in the individual interview cases that were also cited in paired interview cases included *shared objectives* and *frequent face-to-face meetings*. Furthermore, *management intervention* was cited in almost a third of the difficult cases, indicating its importance under those conditions. While *co-location*, *time pressure*, and *trade studies* were also cited relatively often, the N for these factors becomes very small (less than ten), so drawing firm conclusions as to their significance is difficult.

Table 5.5: Individual cases: Citation frequencies of factors facilitating problem resolution.

Factor	Difficult Cases, N Cited (%)	Easy Cases, N Cited (%)
Use of Tests	38 (59%)	19 (58%)
Show and Tell	34 (52%)	14 (42%)
Frequent Face-to-Face Mtgs	16 (25%)	8 (24%)
Shared Objectives/Requirements	9 (14%)	10 (30%)
Use of Trade Studies	8 (12%)	0 (0%)
Time Pressure	8 (12%)	4 (12%)
Critical Team Member	7 (11%)	6 (18%)
Co-location	8 (12%)	7 (21%)
Engineering Expertise	6 (9%)	5 (15%)
Management Intervention	19 (29%)	2 (6%)
Delineation of Tech Iss/Reas Why	3 (5%)	4 (12%)
Development of Win-Win Sol'ns	0 (0%)	3 (9%)

Notes
Percentages indicate number of times a factor was cited relative to the total number of cases of each type. There were 65 Difficult cases and 33 Easy cases.

Combining Easy and Difficult Cases

For the regressions, correlations, and Mann-Whitney analyses that follow, easy and difficult individual-interview cases were analyzed as a group. This was done to increase the number of cases available for each analysis and seemed appropriate given that few significant differences existed between the factors that facilitated problem solving for easy and difficult cases (see section 5.6.2 below and Appendix E). Any cases for which a difficulty level was not indicated were omitted. In addition, only when an interviewee provided both an easy and a difficult case were his or her responses included (so, cases from interviewees that provided only one case were not included).

Correlations

With an understanding of what factors the interviewees considered important based on citation frequencies, the next step in the analysis process was to ascertain if these factors had any effects on the outcome measures. The first method used to assess these impacts was to identify correlations between the factors and the outcome measures. Before that was done, however, an analysis was conducted to test for correlations between the outcome measures themselves. These results are shown in Table 5.6. As can be seen, the measures are correlated. In paired interview cases, satisfaction was positively correlated with cost and schedule impacts. Thus, as might be expected, interviewees were more satisfied with cases that also resulted in positive effects on the product's cost and the program's schedule.

Table 5.6: Correlations between outcome measures.

Measure	In case type	Correlates with...	Correlation Coefficient	Significance
Satisfaction	Paired	Cost Impact	0.513**	0.002
	Paired	Schedule Impact	0.472**	0.003
Performance Impact	Paired	Cost Impact	0.412*	0.015
	Paired	Schedule Impact	0.350*	0.032
	Individual	Schedule Impact	0.262**	0.007
Cost Impact	Paired	Satisfaction	0.513**	0.002
	Paired	Performance Impact	0.412*	0.015
	Paired	Schedule Impact	0.768**	0.000
	Individual	Schedule Impact	0.624**	0.000
Schedule Impact	Paired	Satisfaction	0.472**	0.003
	Paired	Performance Impact	0.350*	0.032
	Individual	Performance Impact	0.262**	0.007
	Paired	Cost Impact	0.768**	0.000
	Individual	Cost Impact	0.624**	0.000

<u>Notes</u>

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

The other three measures, performance, cost, and schedule impacts, were also all correlated with each other. Thus, when problems were solved to the betterment of one measure, the other two also tended to be improved. This also suggests that when a factor that facilitated problem resolution had an impact on one of these measures, it was also likely to have an impact on the other two. To ascertain such effects, as well as their potential benefits to problem solving, Table 5.7, lists the significant correlations that were found between factors and outcome measures.

Table 5.7: Significant correlations between factors facilitating problem resolution and outcome measures.

Factor	In case type	Correlates with...	Correlation Coeffecient	Significance
Management Intervention	Paired	Satisfaction	-0.534**	0.002
	Paired	Schedule Impact	-0.377*	0.039
	Individual	Satisfaction	-0.194	0.074
Use of Tests	Individual	Cost Impact	0.315**	0.004
	Individual	Schedule Impact	0.265*	0.013
Shared Objectives	Paired	Cost Impact	0.405*	0.026
	Individual	Cost Impact	0.283**	0.009
	Individual	Schedule Impact	0.277**	0.01
Co-location	Individual	Performance Impact	0.328**	0.002
Frequent Meetings	Individual	Cost Impact	-0.221*	0.041

Notes
* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Of the factors that had significant correlations with the outcome measures, *management intervention* is perhaps the most notable: it tended to *lower* both satisfaction and schedule impact scores. Given the correlations between the outcome measures themselves, this combined effect is not unexpected. Furthermore, this result is consistent with management intervention's described usage: as discussed previously, this factor was typically used when a team could not resolve a design problem on its own. Management, then, would step in and mandate a solution.

What is perhaps most significant is that management intervention tended to correspond with *lower* schedule impact ratings, i.e., the project's schedule slipped for cases in which management intervened. However, causality is not indicated by the correlation: management intervention most likely did not cause these results. Instead, the results indicate that managers simply did not intervene until teams had already spent considerable time attempting to resolve their problems on their own. At that point, programs were already behind schedule, and managers could do little to accelerate the development processes to make up for lost time.

Use of tests was positively correlated with both cost and schedule impact, though not performance. Thus, teams that used tests were more likely to either improve or at least not degrade their products' cost and their projects' schedules. This finding suggests two important conclusions. First, testing is a useful way to help teams solve problems. Second, although the tests themselves may take time and require money, the overall effect of testing is positive – it does not increase the total time required to solve the problem nor does it increase the product's cost. These results, therefore, indicate that testing is an important and effective mechanism for resolving multidisciplinary design problems.

Shared objectives also demonstrated similar trends, being positively correlated with schedule and cost impacts, but again, not with performance. Thus, shared objectives helped teams stay on schedule and avoid cost overruns, but did not necessarily help them solve problems in ways that enhanced product performance.

Co-location, on the other hand, was positively correlated only with performance impact. This indicates that teams that shared office areas were more likely to solve problems in such a way as to enhance, or, least not degrade, a product's performance. Co-location, therefore, has an important effect on a team's ability to solve problems in terms of the product itself, rather than simply external constraints (such as budgets or schedules).

Finally, *frequent face-to-face meetings* was found to be negatively correlated with cost impact. Given that interviewees were asked to rate the cost impact *to the product*, it must first be noted that the "cost of meeting" is *not* what was being measured. Instead, this result suggests that in cases in which frequent meetings were cited as important, the product's cost tended to be negatively affected. Again, note that this correlation does not indicate *causality*. As suggested by the citation frequency results discussed above, frequent meetings likely took place because of the problems teams were having, and these problems were the likely cause of the increased product costs. It does suggest, however, that meetings were unlikely to help teams avoid these increases in cost, though such increases may have been unavoidable given the problems the teams were confronting.

Another test used to judge the significance of the factors that facilitated problem resolution was to look for correlations between the factors and the unique problem and criteria ratios from the paired cases. The logic behind this decision was that even if the factors could not be correlated with the outcome measures, perhaps there would be a relationship between the factors and how interviewees defined problems. Specifically, the goal was to determine if the presence of any of the factors tended to decrease the unique problem or criteria ratios, or, put another way, if the presence of any of the factors lead to convergence on problem definition. However, no significant relationships could be found.

Regressions

The second method of factor/outcome analysis was to run regressions with the factors facilitating problem resolution and the outcome measures. The details of these analyses are presented in Appendix F. Stepwise models were built for each of the outcome measures (satisfaction, performance impact, cost impact, and schedule impact) and the factors that facilitated problem solving. The models identified key factors that affected each measure, and the most significant results are shown in Table 5.8.

Table 5.8: Predictors for outcome measures identified by stepwise regression models.

Outcome Measure	Predicted by
Satisfaction	Shared Objectives Management Intervention
Performance Impact	Colocation
Cost Impact	Use of Tests Shared objectives
Schedule Impact	Use of Tests Colocation

The results from this regression, not surprisingly, reinforce several of the trends identified by the correlations. Specifically, the relationships between satisfaction and *management intervention*, performance impact and *co-location*, cost impact and *use of tests* and *shared objectives*, and schedule impact of *use of tests* were again revealed. The regressions also identified several additional relationships not found in the correlations: satisfaction and *shared objectives* and schedule impact and *co-location*.

Given the results of the citation frequencies, correlations, and stepwise regressions, six factors seemed to emerge as the most important: *shared objectives*, *use of tests*, *co-location*, *frequent face-to-face meetings*, *management intervention*, and *show and tell*. These six factors were then compared to each other to see further investigate their differences.

Mann-Whitney Tests

As a final statistical test of effects, a multi-step process was used to determine if the presence of one factor led to better performance than another. First, the mean satisfaction and mean performance, mean cost, and mean schedule impact scores were calculated for cases in which a given factor was cited as important. This calculation was made for *use of tests*, *show and tell*, *frequent face-to-face meetings*, *co-location*, *shared objectives*, and *management intervention*, based on their presumed importance (as suggested above). The results are shown in Table 5.9.

Table 5.9: Mean outcome measures for selected factors.

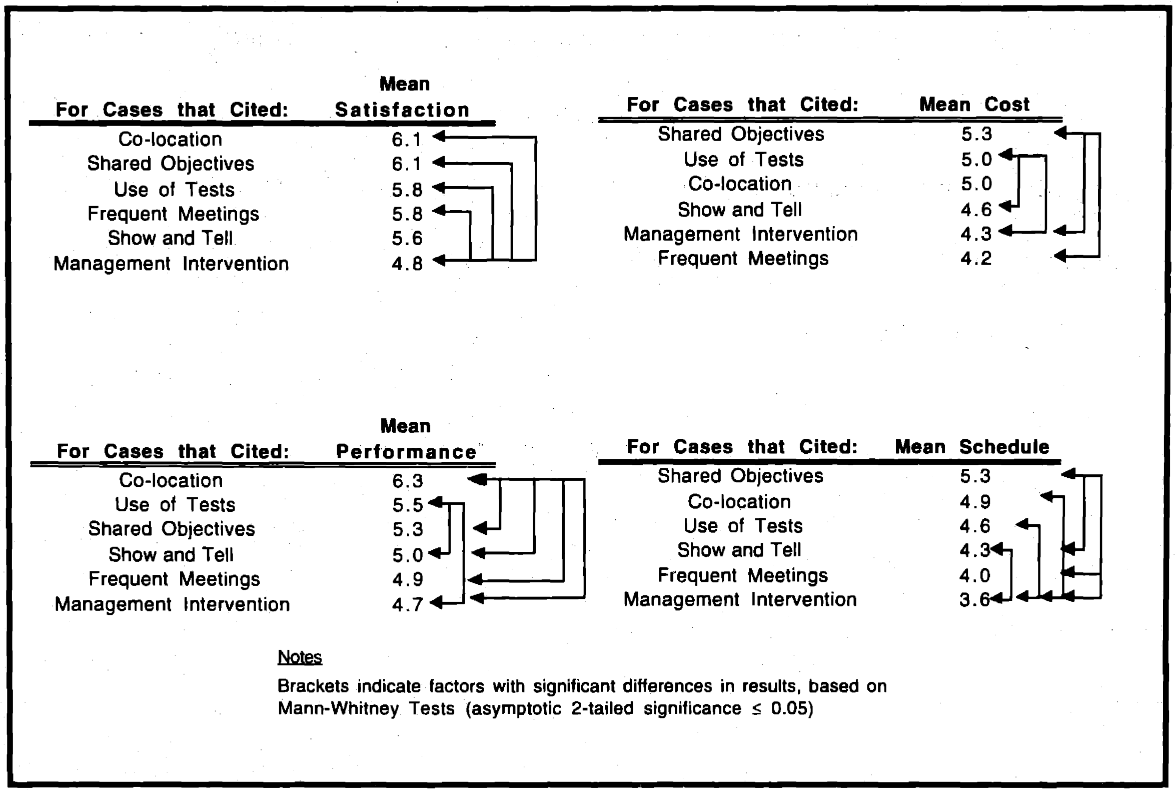
For Cases that Cited:	Mean Satisfaction	Mean Performance	Mean Cost	Mean Schedule
Use of Tests	5.8	5.5	5.0	4.6
Shared Objectives	6.1	5.3	5.3	5.3
Show and Tell	5.6	5.0	4.6	4.3
Frequent Meetings	5.8	4.9	4.2	4.0
Management Intervention	4.8	4.7	4.3	3.6
Co-location	6.1	6.3	5.0	4.9

Notes:
Shaded values indicate highest scores for a given measure.

Next, the factors were rank-ordered based on their mean satisfaction, mean performance impact, mean cost impact, and mean schedule impact, as shown in Table 5.10. To determine if the differences between these scores were significant, Mann-Whitney tests were used to make comparisons between each pair of factors. So, for example, all cases in which *use of tests* was cited as important but *show and tell* was not were compared to all cases in which *show and tell* was cited as important and *use of tests* was not. The details of these calculations are shown in

Appendix D. In Table 5.10, significant differences are indicated by the brackets that link factors in each list.

Table 5.10: Rank order by mean outcome measures of selected factors.



For Cases that Cited:	Mean Satisfaction
Co-location	6.1
Shared Objectives	6.1
Use of Tests	5.8
Frequent Meetings	5.8
Show and Tell	5.6
Management Intervention	4.8

For Cases that Cited:	Mean Cost
Shared Objectives	5.3
Use of Tests	5.0
Co-location	5.0
Show and Tell	4.6
Management Intervention	4.3
Frequent Meetings	4.2

For Cases that Cited:	Mean Performance
Co-location	6.3
Use of Tests	5.5
Shared Objectives	5.3
Show and Tell	5.0
Frequent Meetings	4.9
Management Intervention	4.7

For Cases that Cited:	Mean Schedule
Shared Objectives	5.3
Co-location	4.9
Use of Tests	4.6
Show and Tell	4.3
Frequent Meetings	4.0
Management Intervention	3.6

Notes

Brackets indicate factors with significant differences in results, based on Mann-Whitney Tests (asymptotic 2-tailed significance ≤ 0.05)

As indicated in both sets of tables, cases in which teams had *shared objectives* had the highest mean satisfaction scores and the highest cost and schedule impact scores. Thus, *shared objectives* are clearly an important factor in facilitating team problem solving.

Further, note that *co-location*, *shared objectives*, and *use of tests* always ranked first, second, or third. This general trend indicates that these three factors are among the most important mechanisms for facilitating problem solving on product development teams.

Moreover, *management intervention* always ranked last or second-to-last. This result is consistent with the correlations reported earlier and adds support to the argument that teams that resorted to management intervention were confronting serious difficulties.

Another important trend in the data is that *use of tests* resulted in significantly higher mean performance and cost impact scores than did *show and tell.* Thus, *use of tests* tended to be a more effective mechanism for improving product performance. As is discussed in greater detail below, these two factors differed in two important ways: *use of tests* tended to be more inclusive than did *show and tell*, and *use of tests* tended to keep a problem in its context while *show and tell* tended to remove a problem from its context. These differences appear to have an important effect on the utility of these factors for solving problems.

Also consistent with the correlations presented earlier, *co-location* had a significantly better impact on performance than did *frequent face-to-face meetings.* This result indicates that team members are better able to solve problems when they are physically close to one another than when they must relocate themselves in order to meet.

Given these results, teams that are *co-located*, have well-defined, *shared objectives*, and make extensive *use of tests* are more likely to effectively solve problems than teams lacking these factors. Similarly, teams that must rely *management intervention*, hold *meetings* rather than being *co-location*, or use *show and tell* instead of *tests* will be less able to effectively solve the problems they confront.

Notes on the Outcome Measures

Although multiple factors were identified that facilitated problem resolution, few of these were strongly correlated with the outcome measures. As was discussed earlier, the lack of correlation may be due to an inadequate degree of sensitivity in the outcome measures. Again this lack of sensitivity may be a reflection of the nature of the designs problems that were studied (i.e., all of the problems had be solved) or may be the result of too few cases (only twenty-six paired cases were available, along ninety-eight individual interview cases). Additionally, the analysis is complicated by the fact that multiple factors were often cited by interviewees as important in resolving the problem. Thus, resolving the effects of one particular factor was difficult.

5.5.2. Further Discussion of the Data for Hypothesis Three with Case Examples

Several important conclusions were drawn from the comparisons discussed above. These conclusions can also be reinforced using case examples from the interview data. The following sections review in greater detail each of the six factors analyzed above.

Management Intervention

First, as suggested by the correlations previously discussed, cases in which *management intervention* was cited as important yielded the lowest outcome scores. Again, these results do not suggest that management intervention is the cause of the low scores. Rather, these cases represent the instances in which teams had the most trouble finding solutions on their own.

To test this inference, the rate at which management intervention was cited in easy cases was compared to the rate at which the factor was cited in difficult cases. A chi-squared test was used to judge significance. As shown in Figure 5.4, management intervention was cited significantly more often in difficult cases than in easy cases. This result supports the notion that design teams tended to resort to managers under difficult circumstances. Therefore, while management intervention may tend to result in relatively poor outcomes, it seems as though such results are more reflective of the difficulty of the problems, rather than any lack of skill in managers.

Factor: **Management Intervention**

Number of Times Cited	
Easy	2
Difficult	19

χ^2=6.98	Significant

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	31	2	*33*	
	Difficult	46	19	*65*	
	Residuals	*77*	*21*		*98 =N*

Frequencies		
	25.93	7.07
	51.07	13.93

Figure 5.4: Comparison of management intervention citation frequencies between easy and difficult cases.

Despite these trends, the interview data do suggest ways in which managers can intervene more effectively. Two cases in particular provide some clues. In the first case, a team was tasked to develop a structural modification for a fighter plane that was already in service. The aircraft had been extensively modified over time and had been flown under more strenuous conditions than anticipated during its development, resulting in fatigue cracks in several of its structural components.

An interdisciplinary, co-located team was assembled to develop both replacement parts and a process for removing the worn out components and installing the new ones. An initial solution was proposed by the manufacturing engineers working on the project, but the design engineers rejected the solution. The manufacturing engineers tried, however, to implement their solution despite the objections from the other engineers. The design engineers, therefore, appealed to the team's manager to resolve the dispute. Rather than simply choosing between the alternatives presented by the design engineers and the manufacturing engineers, the manager established a deadline by which the engineers had to reach a consensus on their own. In this case, the two groups of engineers were able to resolve their differences through a series of technical discussions and meetings with the mechanics who would do the repairs.

A second case provides a further example of how managers can successfully intervene to resolve a problem. In this case, a structural engineering design team was developing the preliminary structural design for a new spacecraft. The vehicle had to be designed to endure a wide range of environments, and this requirement substantially complicated the structural design. At several points during the development process, the engineers turned to their manager to resolve technical disputes. In many of these instances, however, the manager did not provide an answer. Instead, he asked the engineers additional questions and forced them to explain the reasoning behind their design decisions to one another. This technique of facilitating discussion allowed the engineers to then resolve their disputes on their own, without the manager having to mandate a solution that would be unsatisfactory to one group or another. The one caveat to this manager's approach, however, was that he was described as a highly skilled engineer. His approach relied on his own thorough understanding of the technical issues that were confronting the team, and only because of this understanding was he able to guide the engineers.

To reinforce the benefits of the approaches described in these two cases, Table 5.11 shows the outcome measures given by the individuals interviewed for these cases. Note that most of the scores are higher for these two cases than for all the other cases that cited management intervention. This result suggests that the techniques used in these cases do in fact yield better results than the typical management intervention technique of decision by decree.

Table 5.11: Outcome measures for alternative management intervention strategies.

Case	Mean Satisfaction	Mean Performance Impact	Mean Cost Impact	Mean Schedule Impact
Manager created time pressure	5.5	6.0	4.0	5.0
Manger asked probing questions	6.0	6.0	N/A	N/A
All other cases that cited *Management Intervention*	4.2	4.5	3.8	2.9

Shared Objectives

Shared objectives also was an important factor in resolving. This result allows for a further interpretation of hypothesis two, that solving problems requires engineers develop a shared understanding of a problem. As was discussed above, no clear relationship could be identified between the extent to which two engineers' interpretations of a problem differed and the performance of their problem solving effort. Based on this result, it was suggested that the reason for this lack of relationship could have been due to the personal nature of the criteria question, namely, that the question specifically asked interviewees to cite criteria important to them. This result led to the additional hypothesis that engineers may have been tempering their emphasis of some criteria based on the needs of other members of the team.

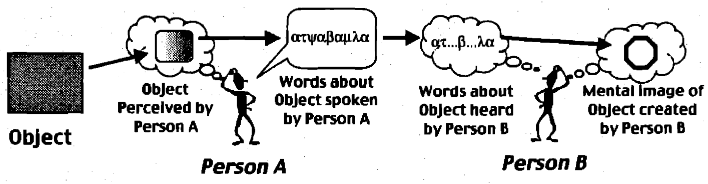
The importance of the *shared objectives* factor may provide support for this hypothesis. As shown in Table 5.10, the presence of *shared objectives* typically resulted in the highest mean cost and schedule impact scores. During interviews, engineers who cited this factor often noted that the problem solving process was made easier by the fact that "everyone understood what the goals were". Because of this understanding, team members were often more willing to make compromises in order to facilitate resolving the problem.

For example, during the development of an aircraft, a problem was identified with a unique aspect of its control system. Specifically, the control system was not providing adequate control margins in the event of a partial failure of the system. As a result, a significant redesign effort was required to correct the deficiency. The development of a solution, however, was complicated by several technical and logistical factors. The critical piece of the control unit was located near the tip of the wing, in an area that was very thin. Consequently, there was not enough space to install a truly redundant control system. Furthermore, neither the prime contractor, nor the second-tier supplier providing the system, had a great deal of experience with the components being used in the new system. Finally, complicating the technical aspects of the problem was the fact that the second-tier supplier was headquartered in another country. Because of the lack of proper technical exchange agreements, the prime contractor could not interface directly with the supplier. Instead engineers from the prime had to work through an upper level supplier that did have the required agreements in place with the second-tier supplier. Despite all of these obstacles, the engineer described the problem solving process as relatively smooth. He noted that because of a "good shared understanding of the goals" of the problem solving effort, "no one [on the team] had any strong differences". Consequently, once the logistical hurdles were overcome, the engineers were able to work relatively efficiently to create a fix created for the control system.

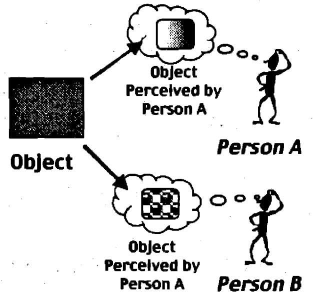
Similarly, as described in 5.2.1 under the discussion of *shared objectives* and *trade studies*, well understood goals or performance metrics tended to facilitate the problem solving process by establishing a shared method of evaluation for potential solutions. Thus, although the criteria considered *personally* important to engineers varied, it appears that engineers also considered a second list, one that included the criteria prioritized by other members of the team. When these criteria were made explicit – such as on decision matrices used in trade studies or when projects operated knowing that cost was paramount – engineers seemed to better understand each other's needs, and, consequently, appeared to be more willing to compromise their own needs in order to resolve the problem.

Use of Tests and Show and Tell

In general, *use of tests* and *show and tell* facilitated problem resolution by allowing engineers to develop a shared interpretation of the problems they were addressing. By providing a physical object (or a representation of a physical object such as on a CAD display), tests and models helped to facilitate "silence on the objective level" – they allowed individuals to *point* to something rather than to try to use words to describe something. This decreased the number of abstractions used during communication, eliminating several stages of interpretation, summary, and inference (see Figure 5.5). As a result, the individuals sharing models or conducting tests together started their abstractions from the same, objective level. Consequently, their ability to solve a problem improved, since they were able to develop a more closely shared understanding of what the problem itself was. Furthermore, since their lower order abstractions were now more similar, their higher order abstractions, such as judgements about the suitability of a solution, were also more similar.



Chain of abstractions when no object shared between Person A and Person B.



Chain of abstractions when an object is shared between Person A and Person B.

Figure 5.5: Comparing the abstraction process when an object is and is not shared between two people. Sharing an object reduces the chain of abstractions, facilitating more similar interpretations.

A design team developing concepts for a new car's exterior provides a good example of the concepts shown in Figure 5.5. During early discussions about the car, the stylists stated their preference for a design that featured many "sharp" angles and "crisp corners". The manufacturing engineers on the team immediately objected, noting that such features would be difficult to produce. They argued in favor of much smoother surfaces, with more "open" corners. This disagreement rapidly brought the team's progress to a halt, as the two groups argued back and forth. To help end the debate, one of the more senior and experienced manufacturing engineers on the team ordered a full-scale clay model be built of one the components on which the debate focused. As an engineer who worked on the team described, once the model was in front of people, the team had much more effective discussions. Specifically, he noted that the shift from words and numbers to a physical object clarified the points both sides were trying to make, and allowed the groups to begin to move toward a consensus about the design.

While both *show and tell* and *use of tests* have clear benefits, as previously noted, *use of tests* resulted in significantly higher mean performance and cost impact scores than did *show and tell.* Understanding these differences requires understanding how models or other objects were used in the case of *use of tests* compared to *show and tell.*

Recalling the discussion in section 5.2.1, there are two primary distinctions between *use of tests* and *show and tell.* The first important difference between these two factors centered on the extent to which the team participated in their creation. Typically, tests were either witnessed by the entire team or the team as a whole agreed in advance to conduct the test. *Show and tell,* in contrast, referred to instances in which prototypes, models, or even test results were created by one member or subgroup of a team and then *presented* to the other members of the team. Thus, *use of tests* typically indicated a more inclusive, participatory event while *show and tell* was more passive. The second difference between these two factors related to context. *Use of tests* required that some representation of the design (a prototype, for example) be subjected to an environment that would mimic the environment experienced by the final design (such as a wind tunnel or computer simulated environment). *Show and tell,* in contrast, was usually divorced from such contexts – a prototype part was simply brought to a meeting and pointed to by members of the team.

These differences in degree of participation and context are the likely causes of the significant outcome measure differences between *use of tests* and *show and tell.* When agreeing to conduct a test, a team was effectively agreeing to a shared standard of evaluation, whether they explicitly stated that standard or not. The process of conducting a test required that a team first agree on what the problem was that required testing and then required that the team agree to a data collection approach. That data collection approach, in turn, established an evaluation system. By choosing to gather information on some variables and not others, the team declared those variables to be most important, and, by using that information to guide later design decisions, those variables framed an evaluation system for the team.

In contrast, *show and tell* did not require the development of such an evaluation system. In fact, *show and tell* placed control of the evaluation system in the hands of the individuals who brought the object to the other members of the team. Rather than allowing other members of the team to help shape an evaluation system, the model could be used by one person or group to limit and restrict the number of possible interpretations of the problem. The importance of participation can be illustrated by comparing two cases that attempted to make use of tests.

Consider first a case in which *use of tests* was used to facilitate the development of a shared evaluation system. In this case, manufacturing engineers were attempting to implement lean manufacturing techniques on a composite component manufacturing area. The line operators, however, were relatively resistant to these efforts. They considered themselves craftsmen, and the new methods would make their work much more mechanistic. Under the old approach, each operator was responsible for the complete lay-up of a component. The new approach, in contrast, required that multiple operators work together to build a part. Consequently, the operators felt as though they would have less control over the quality of their work and believed their talents as skilled workers would be compromised.

Rather than attempting to force a new manufacturing method on the operators, the engineers set up a prototype operation – referred to as the “lab” – next to the old one. The engineers then asked the line operators to come experiment with the new set-up and express their opinions about its performance. Gradually, the engineers refined the design of the new manufacturing operation based on the input of the line operators, and ultimately the new design was implemented on the production line. One of the manufacturing engineers involved with the project credited the lab with being a key factor in facilitating the line worker's acceptance of the new operation. Allowing the workers to actively participate in the development of the new manufacturing method enabled them to feel that their opinions and skills were valued and gave them a sense of having designed the new method to suit their own needs.

In contrast, *use of tests* in another manufacturing-related case did little to facilitate solving a dispute. In this instance, a group of research and development manufacturing engineers wanted to install a new riveting tool on an aircraft component production line. The new tool allowed for more control over the forces applied to a rivet than did the old machine. This additional level of control would allow the riveting operation's speed to be increased, shortening the cycle time needed to assemble several components. A multidisciplinary team was formed to investigate the feasibility of installing the new machine on the production line.

Several members of the team, most notably the materials and processes (M and P) engineer, expressed serious reservations about the machine and its riveting method. The particular point of contention related to how the machine applied force to a rivet over time, referred to as the force profile. The new machine changed this profile, shortening the duration of the force that was applied to a rivet. These changes, in turn, facilitated the higher cycle times for the machine. The M and P engineer, however, believed that the old force profile and its duration was critical to the fatigue life of the assembled components. He argued that the proposed changes to the force profile would reduce the component's strength, leading to potentially catastrophic failures during the product's operation.

In an effort to alleviate these concerns, several of the manufacturing engineers independently conducted coupon tests[3] with the new machine and assessed a variety of variables through the use of design of experiments (DoE)[4]. They then analyzed the riveted test coupons to compare the results of the new riveting process to the old, and these results were then presented to the team.

By this point, the debate had become very heated. As one manufacturing engineer who worked on the project recalled, one of the engineers who conducted the testing slammed a coupon onto a table in front of the group and declared, "See, it works!" To this day, a small dent remains in the table. Thus, rather than being a process in which the whole team participated, the test results were presented in a *show and tell*-like fashion. And, despite this show of emotion, the M and P engineer remained unconvinced. He did not believe that the tests adequately represented the issues about which he was concerned, namely, the rivet's fatigue strength over time. In other words, in his mind, the tests did not represent his evaluation system. His distrust of the results was exacerbated by the fact that he was not trained in DoE. Consequently, he did not understand how it could be used to demonstrate interactions between variables, interactions that addressed his concerns. No matter how accurate the tests may have been, his lack of confidence and understanding of their results meant that the tests held little significance for him. Because of his objections, the effort to install the new machine ultimately failed.

From the perspective of this research, the important point is that the testing that was done failed to fully accommodate the evaluation systems of all of the members of the team in way they all could understand. Rather than allowing the team to agree to a standard of evaluation, the

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[3] Coupon tests are experiments that use representative pieces of material, rather than complete parts, to demonstrate the operation of a manufacturing process.

manufacturing engineers tried to control that standard, in effect declaring that the coupon tests adequately illustrated all of the important issues surrounding the dispute. But the M and P engineer did not agree and felt that the tests failed to properly address his concerns about the fatigue life of the rivets. Consequently, tests that could have been definitive were not, and their results proved unhelpful in resolving the dispute.

A study by von Meier (1999) revealed very similar trends. Von Meier investigated communication patterns between engineers and operators at electric power distribution companies. She found that the two groups had different cultures and that they evaluated technical problems using different criteria. Furthermore, as in the example discussed above, von Meier noted that the two groups were swayed by different types of evidence during arguments: "the engineer is convinced by abstract analysis, whereas the operator trusts only direct experience" (p. 109). The differences between the M and P engineer and the manufacturing engineers at the aircraft company are a close parallel those of the operators and engineers discussed by von Meier: the M and P engineer only trusted his own experience, while the manufacturing engineers were accustomed to the more abstract test results.

In other cases *use of tests* proved helpful in resolving problems because it focused teams on analyzing some aspect of a design in its operational context (or a simulation thereof). As was previously discussed, much of what a person knows is context specific. Thus, a person can better express what he or she knows when that knowledge is applied to a specific situation. Tests facilitated such opportunities for members of design teams. Rather than having to guess how a design solution might perform under a given set of conditions, tests allowed teams to actively witness how their designs performed in operation. By placing a problem in an operational

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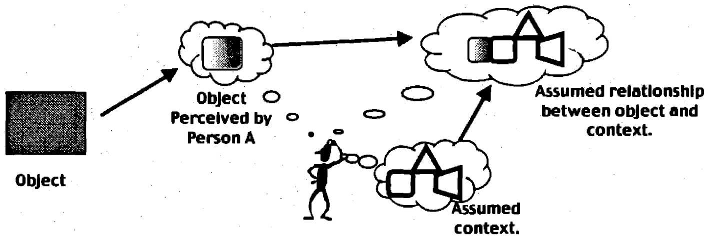
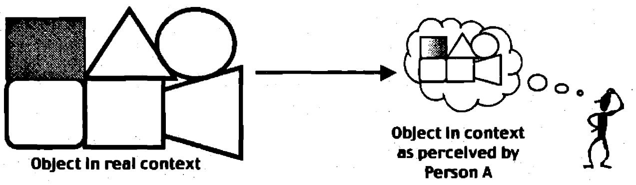
[4] Design of experiments is an experimental approach that uses mathematical relationships to reduce the

context, a layer of interpretation and supposition was removed from a debate, and the chain of abstractions was reduced (see Figure 5.6). Examples help to demonstrate these concepts.



Chain of abstractions when object is divorced from context.



Chain of abstractions when an object is shown in context.

Figure 5.6: Comparing the abstraction process when an object is and is not represented in its real context. When an object is represented in context, fewer abstractions are required to understand its relationship with its surroundings, reducing the likelihood of error.

During the assembly of several aircraft components, line operators discovered that they could not install shim plates that were called for on the assembly drawings. The problem was that the operators did not have enough space to physically reach the location where the shims were to be placed. Engineering was alerted to the problem. They were initially surprised by the difficulties the operators were having – according to their drawings, the shim should fit without problem.

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number of experiments that are required to test for the effects of a large number of variables.

The reason the engineers failed to realize that their design would cause such trouble on the factory floor was that their design process had not accounted for the dynamics of the assembly process. The engineering drawings showed that once assembled, all of the parts fit together. Nevertheless, the drawings failed to demonstrate how those parts would come together during the assembly process – the drawings failed to capture the *context* in which the shim would be installed. In real life, several other components blocked the operators' access to the shim's location. This problem was verified by the engineers during visits the factory floor to observe the assembly process and by using three dimensional computer models to simulate the assembly sequence. With the dynamics of the problem clearly demonstrated, the engineers were able to quickly develop a modification to a nearby part to facilitate access to the shim.

This example clearly demonstrates the importance of capturing the complete context of a design during problem solving. Represented as a fully assembled part, the drawings did not even reveal that a problem existed. Only once the dynamics of the assembly process were included did the engineers realize their oversight. Hence, the test in this case was when the line operators actually assembled the parts for the first time, revealing the problem. Subsequently, the computer models of the parts were also used for additional testing, allowing the engineers to experiment with methods for correcting the problem. Thus, the inclusion of the proper details of the context in which the shim was to be installed was essential to recognizing and resolving the design problem.

So, the primary differences between *use of tests* and *show and tell* lie in the extent to which an entire team participated in the creation of an object and the extent to which the object was represented in its operational context. These differences, then, are the source of the higher outcome measure scores for cases that cited *use of tests* compared to cases that cited *show and* *tell.* By more fully capturing the details of a problem and by ensuring that the team reached a consensus on how to evaluate potential solutions to a problem in advance, *use of tests* provided a clear and definitive mechanism for teams to resolve their differences.

Co-location and Frequent Face-to-Face Meetings

Co-locating the members a product development team is a technique that has been advocated by many researchers over the years as a means of facilitating improved cross-functional communication and integration (see, for example, Allen, 1988). The results of this study join those previous investigations in advocating its use. Importantly, this study was also able to demonstrate that frequent meetings are not an adequate substitute for co-location. As discussed above, *co-location* had a significantly better effect on performance impact scores than did *frequent face-to-face meetings*. Thus, meeting regularly does not serve as a replacement for sharing an office space.

The benefits of *co-location* and *frequent face-to-face meetings*, however, appear to originate from the same foundation. Both of these factors allowed team members to get to know each other and one another's concerns. By meeting regularly, the engineers got to know each other as people, and this social familiarity helped to facilitate their technical communication and problem solving. Typically, additional factors such as *show and tell* or *use of tests* supplemented discussions during this socialization process. Over the course of their meetings or co-location, the different groups also learned to trust each other's technical skills, and this gradual development of trust improved their abilities to work together.

A good example of *frequent meetings* coupled with *show and tell* is provided by the design and development of a new overhead crane for use an aircraft manufacturing factory. In addition to a variety of technical requirements, management had mandated that the crane's controls be designed to reflect the input of the crane operators. To meet this mandate, the electrical engineers developing the control system held a series of meetings with the crane operators. At each meeting, the engineers brought with them a laptop computer on which they showed computer-generated illustrations of the crane's controls and displays. The operators then critiqued the design, and the engineers subsequently updated the controls to reflect the additional input. This back and forth process of design, meet, and critique continued until the end of the crane's development project.

Meetings were also used in another fashion: as design reviews. During such reviews, experienced engineers who were respected for their technical skills were invited to witness presentations made by design teams. These experts were then asked to note if the team had made any mistakes or if there were issues that the team had failed to address. The experts also tended to share lessons they had learned on past projects that might be applicable to the challenges being faced by the team. In this manner, such meetings served as checkpoints during the development process to ensure the quality of a design team's efforts.

5.5.3. Conclusions Regarding Hypothesis Three

So, does the data presented in the preceding sections refute or support hypothesis three and its suggestions as to the benefits of some tools over others in facilitating problem solving? Based on the results and cases reviewed above, it would appear that the hypothesis itself misses the important issue. What affects the success or difficulty of design problem solving is not *what* tool is used, but *how* the tool is used. Thus, a leaf blower helped to facilitate one design team's efforts by illustrating the *problem* faced by the team, while a clay model helped to clarify a potential *solution* for another team. Similarly, tests run with the full involvement of line operators helped facilitate the development of new manufacturing methods, while the lack of involvement of some members of a team prevented the installation of a new riveting tool, despite tests demonstrating its potential benefits. Three common themes emerge from the cases in which tools facilitated problem solving: (1) they were used in a highly inclusive, participatory fashion, (2) all of the important elements of a problem's context were captured in the tool's use, and (3) through the use of such tools, the team was able to agree to a shared evaluation system used to judge potential solutions.

In summary, then, design tools such as prototypes, test results, or CAD models appear to offer their greatest benefits when they are used in a participatory fashion and when they capture the full context of the design problem. In contrast, when the same tools are used by one side of a design dispute to unilaterally "prove" that they are correct, or when important elements of the a problem's context are omitted, their potential benefits appear to be significantly lessened.

5.5.4. Further Discussion of Participation and Shared Evaluation Systems

As noted above, the results of this study indicate that *what* tool is used to help solve a dispute is less important than *how* the tool is used. Specifically, it was argued that using a problem solving tool effectively required that the team use the tool together to create a shared understanding of the problem and a mutually agreed to evaluation system for judging potential solutions' benefits or drawbacks. Support for these conclusions can be found in a variety of other studies.

Many other researchers have investigated the benefits of different problem solving approaches, and, in general, support the use of participatory, or cooperative, strategies. Typically, the literature distinguishes between three types of problem solving methods: (1) cooperative (also often called collaborative or constructive, and in this study termed "participatory"), (2) passive (or avoidance), and (3) aggressive (or competitive or forceful). As Griffin and Hauser (1996) concluded in their review of the problem solving literature, "[t]he evidence [in support of cooperative problem solving methods] is strong, consistent, common across a variety of methodologies, and seemingly applicable in both services and products and in both consumer and industrial markets" (p. 193).

For example, in Cooke and Szumal's (1994) study using a simulated survival exercise, teams that used constructive methods to resolve conflicts were more effective problem solvers than those who used passive or aggressive styles. Similarly, Gobeli et al (1998), in a survey of 115 software development professionals, found that confrontational problem solving strategies (e.g., strategies that encouraged team members to openly and constructively explain their reasoning) had beneficial effects on team performance while forcing strategies (in which one side of dispute demanded the other side accept its solution) had negative effects. Such trends appear to be fairly consistent across cultures as well. Xie et al (1998), for example, surveyed 968 marketing managers in Japan, Hong Kong, the United States and Great Britain, and concluded that of three possible strategies – collaboration, avoidance, or conflict – collaborative methods produced the best results.

In addition, several studies have specifically cited the need for team members to actively participate in the problem solving process. For example, in a study by Berardi-Coletta et al (1995), researchers found that simply providing hints, explanations, or demonstrations of solutions did not help problem solvers find the answer to an experimentally-controlled problem. Instead, they discovered that "information regarding the problem solution must be acquired or discovered by the participant" – only by actually participating in the problem solving process could the subjects solve the problem.

Such trends seem to also apply to product development teams. For instance, based on a review of the management literature, Cohen and Bailey (1997) concluded that the "substantive participation" of technical specialists on teams led to better performance than when specialists participated on teams in a "consultative" role. Similarly, in their study of automotive and aerospace product development teams, Lucas et al (2000) found that "active participation" of team members was a significant factor in preventing teams from making mistakes and avoiding costly delays.

A variety of researchers have also advocated the shared use of tools, as suggested by this study. Wenger (2000), for example, recommended an approach which he refers to as "engagement". He noted that the process of producing artifacts together served as a way for team members to learn what they each could do and how their actions would influence others' reactions. Similarly, Henderson (1991) and Carlile (1997) found that the act of jointly creating and sharing objects such as sketches or prototypes facilitated conflict resolution on product development teams. As Henderson (1991) noted, such objects "enlist group participation and are receptacles for the knowledge created and adjusted through group interaction" (p. 456). And, in their study of 40 new product development projects at 15 firms, Adams et al (1998) found that data from test results were more believable to team members when they participated in its acquisition. Thus, they argued, "[b]road and active participation throughout the [product development] process will enable the development of a shared mental model and the dissemination of information based on a common understanding of its contribution to the objectives and priorities of the project" (p. 418).

The importance of such shared mental models and objectives has also been demonstrated by other researchers. In addition to the work by Adams et al cited above, studies by Bailey (1999), Gobelo et al (1998), Lynn et al (1999), McDonough (2000), Pelled and Adler (1994), and Rusinko (1999) have all found that the presence of well-known, shared team objectives was an indicator of high performing product development teams. Importantly, as a group these studies indicate that shared goals were important across technical specialties, including product designers, product development managers, manufacturing engineering managers, and software developers. That shared goals have been indicated to be important across specialties reaffirms their importance during multidisciplinary problem solving. Shared goals allowed teams to develop a shared representation of the problems which they faced, and such common understandings then facilitated their efforts to find a solution to the problem.

Along this line of reasoning, Tindale et al (1996) suggested that the development shared representations among team members was at the root of the members' ability to solve problems together. They proposed that there were four elements required for a group to solve a problem together:

> (1) A shared verbal or mathematical system for solving the problem.
> (2) Sufficient information to demonstrate that one answer correctly solves the problem.
> (3) Group members not directly involved in solving the problem must have sufficient knowledge of the system to recognize a correct answer when one is proposed.
> (4) Members who solve the problem correctly must be able to demonstrate that answer to those who solved the problem incorrectly. (Tindale et al, 1996)

When members of a group all shared these elements, the researchers argued, the group was more likely to agree to a solution. Furthermore, the representation to which they agreed influenced and limited how easy or difficult it was for a team member to argue for or against any one potential solution. Thus, if an incorrect answer was more easily demonstrated using the team's shared representation, it was more likely to be chosen over correct answers.

Tindale et al (1996) used this model of problem solving to explain a wide range of previous psychology study findings. For example, previous studies using mock juries had found that manipulating a judge's instructions to the jury affected the jury's verdict, even if the same evidence was presented. Such an outcome is predictable according to the shared representation model presented above. In these cases, the judge's instructions formed the basis of the jury's shared representation. Altering those instructions altered the jury's shared representation, and affected what arguments (in favor of a guilty or innocent verdict) seemed more plausible. Similarly, Tindale et al (1996) suggested that the "risky shift" phenomenon in groups was explainable using shared representations, as were group decision errors.

The importance of such a shared representation has also been argued as facilitating the formation of a strong sense of team identity. Walsh (1995), for example argued that "a shared cognitive map emerges from a social process marked by negotiation and argument" among team members (p. 293). Although the team members initially join the group with very different opinions about the problem, through their interactions their models of the problem grow to include issues raised by other individuals on the team. Furthermore, Scott (1992) studied 42 product and process development teams across three divisions of a Fortune 500 company and concluded that team members' social identification with their team had a "critical influence on team performance" (p. 120). Specifically, the basis of group identification in high performing teams "did not appear to be personalized bonds of attachment among team members but impersonal bonds derived from the common identity of 'project team member'" (Scott, 1992, p.

122). This identity was likely derived in part from the shared representations held by the team members of the problems that they faced.

Therefore, Tindale et al's model, along with the results of the studies discussed above, all lend support to the conclusions reached during this investigation. As was argued, the process of running a test or creating a prototype together allowed team members to agree to a shared evaluation system that they could then apply to solving the problem. Thus, through a *cooperative process*, the team agreed to a *shared set of goals*, in turn creating *a shared representation* of the problem. Once this shared representation was in place, the team members had a common system of meaning and evaluation that they could use to develop a mutually acceptable solution. On the other hand, teams that failed to develop such a shared system proved less effective in solving the problems they faced.

5.6. Additional Observations

Several additional issues from this study are worthy of note: how alternatives were considered during problem solving, other differences between easy and difficult cases, and some observed differences between how engineers solved problems and how manufacturing personnel solved problems.

5.6.1. Consideration of Alternatives

As discussed in section 4.1.2, several studies have suggested that considering more than one design alternative at a time can help facilitate problem solving. While this study did ask interviewees to indicate the number of alternatives they considered and the manner in which those alternatives were evaluated, no significant relationship could be found between those approaches and the outcome measures. Table 5.12 lists citation frequencies for these approaches. Note that in both easy and difficult cases, the most often cited approach was the serial or iterative evolution of one alternative. Parallel consideration of three or more options in parallel was cited next most frequently, followed by parallel consideration of two alternatives. The tendency suggested by this data is that when engineers do consider multiple options, they usually consider more than three at a time. But, as stated above, no indication of any potential problem solving performance benefits of the different strategies were identified by this study.

Table 5.12: Citation frequencies of various design strategies.

Case Type	Interviewee	Number of Times Cited	Percentage
Easy	Iterative/serial development of one option	17	52
	Parallel consideration of 2 alternatives	5	15
	Parallel consideration of 3 or more alternatives	9	27
Difficult	Iterative/serial development of one option	28	43
	Parallel consideration of 2 alternatives	12	19
	Parallel consideration of 3 or more alternatives	22	34

Notes:
There were 33 Easy cases and 65 Difficult cases. Percentages are relative to these total values.

One potential explanation for the tendency towards considering only one design at a time is that in a team environment, people can better focus on solving a problem when they consider one solution rather many. For example, a study by Laughlin and Bonner (1999), found that while an individual's problem solving performance increased when he or she considered more hypotheses, a group's performance was improved with *more evidence* and *fewer hypotheses*. That is, in a group environment, teams that considered fewer hypotheses at a time, but that collected more evidence on each, performed better than groups that attempted to consider a large number of hypotheses in less detail.

Such trends may explain the results of this study. In a team environment, product developers were better able to convince each other of how to solve a problem by considering only a few potential solutions in great detail, rather than trying to analyze many possibilities. Thus, while developing sets of alternatives may work well at a high level, detailed problem solving might be better facilitated by considering fewer options. Clearly, however, the results of this study on this topic are far from definitive, but they do suggest avenues for future investigations.

5.6.2. Other Differences between Easy and Difficult Cases

Several comparisons have already been made between easy and difficult cases. It is worthwhile, however, to consider some of the other differences between the two types of cases as well. These differences suggest that the source of difficulty in solving problems on teams may lie more with social, rather than technical, factors.

Table 5.13 lists the mean outcome and demographic measures for easy and difficult cases. While *satisfaction* scores tended to be higher for easy cases, the other performance measures are similar for both types of cases. Several issues are raised by the demographic measures, however. First, the *average previous experience with similar problems* scores are not very different between the two types of cases. Thus, an individual engineer's past experience solving similar problems is *not* necessarily an indicator of whether or not a problem will be viewed as difficult.

Table 5.13: Comparison of mean outcome and demographic measures for easy and difficult cases. (Shaded values are the higher of the two scores.)

Measure	*Case Type*	
	Easy	**Difficult**
Mean Satisfaction	▨ 6.2	5.2
Mean Performance Impact	5.5	5.1
Mean Cost Impact	4.6	4.6
Mean Schedule Impact	4.7	4.2
Previous Experience with Similar Problems	4.5	4.4
Complexity (social and technical)	4.6	▨ 5.4
Previous Experience with Other Members of the Team	▨ 4.3	3.4

Looking at the mean *complexity* and *previous experience with the team* scores, however, is more revealing. On average, difficult cases were rated as more complex, and interviewees had had less experience working with the other members of the team, than compared to easy cases. Recall that the complexity question asked interviewees to estimate complexity accounting for both social and technical factors. Thus, when combined with the lower mean *previous experience with the team* score, these two measures suggest that difficult problems were rated as such less for their technical challenges than for their social challenges. That is, difficult problems tended to be difficult because of the social interactions within the team, rather than because of the technical problems faced by the team.

This notion is reinforced when looking at the citation frequencies for factors that hindered problem resolution (see Table 5.14). While all of the negative factors occurred more frequently in difficult cases than in easy ones, both *social problems* and *lack of shared metrics or objectives* occurred significantly more often, based on chi-squared tests (see Appendix E). Note that both of these factors are directly related to the social interactions on the team and not technical issues. The frequency with which they occur, therefore, supports the notion that difficult cases were difficult because of the social challenges faced by the team, rather than the technical ones.

Table 5.14: Comparison between easy and difficult cases of citation frequencies for factors that hindered problem resolution. (Shaded factors indicate statistically significant differences.)

	Easy		**Difficult**	
Hindering Factor	*N*	*Percent*	*N*	*Percent*
Social Problems	5	15	*27*	*42*
Misuse of Boundary Object	1	3	6	9
Lack of Shared Metrics	0	0	*11*	*17*
Unclear Lines of Comm.	2	6	11	17

One potential limitation to this conclusion, however, stems from the instructions given to interviewees. As previously described, participants were told that difficult cases could be characterized less by technical challenges than by social ones. Thus, interviewees may have been biased to describing cases that were socially challenging, instead of describing cases that were technically challenging. In that sense, the data do conclusively show that the interviewees tended to understand the instructions. Asserting that, in general, difficult problems are difficult more for social than for technical factors, however, may be less firm a position. On the other hand, given that product developers were able to provide so many cases in which social challenges dominated technical ones does suggest that such tendencies are less than rare.

Table 5.15 lists the citation frequencies for factors that facilitated problem resolution for easy and difficult cases. As previously discussed, *management intervention* occurred significantly more often in difficult cases than in easy ones. Note also that *trade studies* were conducted significantly more frequently in difficult cases as well. Again, such a result is not necessarily unexpected. Difficult cases, by their nature, forced engineers to make compromises, and trade studies are a common tool to help engineers make such decisions. The fact that trade studies were never used in easy cases reinforces the idea that such cases involved few, if any, difficult tradeoffs. Finally, *win-win solutions* were only developed for easy cases. Because such cases tended to be simpler, engineers were more often able to develop solutions that simultaneously addressed multiple needs. Such achievements were less possible in difficult cases because such cases were often characterized by either-or types of choices.

Table 5.15: Comparison between easy and difficult cases of citation frequencies for factors that facilitated problem resolution. (Shaded factors indicate statistically significant differences.)

	Easy		Difficult	
Facilitating Factor	*N*	*Percent*	*N*	*Percent*
Management Intervention	2	6	*19*	*29*
Critical Team Member	6	18	7	11
Engineering Expertise	5	15	6	9
Trade Studies	0	0	*8*	*12*
Show and Tell	14	42	34	52
Use of Tests	19	58	38	59
Time Pressure	4	12	8	12
Co-located Team	7	21	8	12
Frequent Meetings	8	24	16	25
Shared Objectives	10	30	9	14
Win-Win Solution	*3*	*9*	0	0
Reason Why	4	12	3	5

5.6.3. Differences between Engineering and Manufacturing Problem Solving

While no quantitative data were collected on this topic, several significant differences were observed between the problem solving approaches typically used by engineers and those used by manufacturing personnel. These differences centered on the degree of formality in the problem solving processes of the two groups. In general, when discussing their efforts to improve their production processes or to correct problems on the factory floor, manufacturing personnel would refer to a standardized problem solving approach used by the company. Such approaches typically required a formal contract be written and then signed by the team that stated what the problem was and how the team members were expected to behave during meetings (for example, to refrain from criticizing an idea during brainstorming sessions). In addition, these formalized processes also tended to specify how many alternatives should be considered, the rate at which alternatives should be eliminated, and the degree to which they should be developed. For example, at one factory site, the problem solving process mandated that a problem solving team initially generate at least seven ideas. Furthermore, all ideas had to be illustrated, no matter how bad people's drawing skills were, rather than described using words. Once the seven ideas were developed, these were then slowly narrowed to two, based on discussion or rough analyses. Prototypes of the remaining two options were then built in order to further develop the ideas. Finally, one option was selected, and its prototype refined prior to building production-quality equipment.

This concept development process also highlights another important difference between typical engineering problem solving and manufacturing problem solving: manufacturing personnel seem to place more emphasis on visual or physical representations of their ideas. Whereas many engineers informally complained about "spending too much time in meetings" during their interviews, none of the manufacturing personnel expressed similar problems. Rather than meeting to discuss problems, manufacturing personnel seemed to place more emphasis on experimenting with new ideas. Clearly one reason for this increased emphasis on experimentation was the result of the relatively low availability and use of manufacturing-related computer simulation or analysis tools. In addition, many of the manufacturing problems were hard to simulate on a computer. Thus, the only way for manufacturing personnel to address their problems was via direct experimentation.

Finally, although manufacturing problem solving processes appeared more formalized than engineering processes, the results produced by such approaches seemed no less creative. Instead, the formalization of the process prevented time being wasted on establishing how a team will go about its task and allowed the team to focus its energies on the problem itself. Furthermore, because the process was explicit, people better understood what was expected of them, and this understanding allowed the teams to work more effectively.

In contrast, engineers rarely referred to any standardized approaches to addressing the problems they confronted. One argument that could be used to explain this lack of formalization is that the wide variety of problems confronted by engineers do not lend itself to standardized approaches. The few cases that cited *trade studies* as an important factor, however, demonstrate that such an argument is not valid. While the interviewees who described trade studies did not describe processes that were defined to the same level of detail as in many manufacturing cases, they did describe a common process of first developing a list of evaluation criteria, then creating a set of design concepts, and, finally, running tests or analyses to compare those concepts against the criteria. Thus, engineering design problem solving processes clearly can be standardized. Future investigations might examine this possibility, and its effects on problem solving performance in greater detail.

6. RECOMMENDATIONS AND SUMMARY

6.1. Recommendations for Practitioners

The ultimate aim of this research was to improve the ability of design teams to solve problems, and thereby improve the ability of product development firms to compete successfully in the marketplace. Given the results of this research, several practical recommendations can be made to practitioners in the product development business.

6.1.1. Agree on the Problem, then the Standards for Evaluation, then the Solution

The most fundamental result of this investigation was to demonstrate that two engineers are likely to interpret the same problem differently. Furthermore, their differences in interpretation likely will include differences in exactly what they believe the problem to be and how potential solutions to the problem(s) should be evaluated. Given this finding, engineers working on design teams should work from the assumption that what they consider a problem may not, in fact, seem like a problem to other members of the team. Conversely, engineers need to be ready to accept that something that does not seem like a problem to them may be a significant issue to another engineer on the team.

Therefore, when team members are confronting serious difficulties in resolving a design problem, they should ask two questions: (1) Does everyone agree on what the problem is that they are trying to solve, and (2) How do they differ in the manner in which they are evaluating potential solutions to the problem? Explicitly addressing such differences could reveal that the actual source of the disagreement is not based so much on irreconcilable opinions as it is on a difference in how the problem itself is being framed.

Finally, the more explicitly a team's goals and requirements are defined at the start of a problem solving effort, the more effective the team will be. By clearly establishing the team's objectives from the outset, all members of the team begin the problem solving process from the same reference point. More importantly, such shared objectives create a shared evaluation system among the team members, meaning that they are more likely to evaluate a potential solution in the same way. Thus, some of the more divisive effects of each individual's interpretations are avoided, facilitating communication during the problem solving process.

6.1.2. Successful Management Intervention

This study found that it is not always possible for design teams to resolve design disputes on their own – at times, management intervention may be required to help a team end a disagreement. However, some methods of intervention yielded better results than others. Whenever possible, managers should seek to facilitate additional problem solving by the team itself, rather than mandating the use of a particular solution. For example, such facilitation can take the form of a series of technical questions that are put before the team for its members to investigate (perhaps through additional testing) or by giving the team a new, closer deadline by which they must come to an agreement on their own. In general, the guiding principle for managers under such circumstances should be to seek additional ways of getting the team members to work together, rather than taking the decision process out of their hands.

Note that such approaches require that managers have a good technical understanding of the problems being addressed by their team. Consequently, another recommendation from this research is that design teams should be managed by individuals who are respected for their technical, as well as business, abilities. Managers who lack such skills will be forced to rely solely on the arguments of the different sides of a dispute, and will be unable to objectively and knowledgeably chose between them.

6.1.3. How to Use Design Tools

Given how differently engineers may frame a problem, it is important that design tools be used in a fashion that reflects and allows for such differences. Several methods are available to facilitate this goal.

First, the closer the representation of a problem is to its real form, both in terms of the appearance and functionality of the design, the better. Thus, a physical prototype part is likely to be preferred to a drawing when attempting to demonstrate what a part will look like. On the other hand, a computer simulation may better demonstrate the *process* needed to assemble the parts than a prototype part could. Consequently, engineers must be aware of the tradeoff they may make in terms of accurately representing what a design might look or feel like compared to accurately representing how a design might behave.

Furthermore, the choice of representation must also be influenced by the degree of familiarity other members of the team may have with a given tool. As several cases demonstrated, when team members can readily interpret the meaning of a representation, they are more likely to accept conclusions drawn from it. Thus, a leaf blower proved to be an effective method of demonstrating aerodynamic principles to engineers without backgrounds in aerodynamics, whereas a computation fluid dynamics simulation would have been far more difficult for them to comprehend.

Finally, in order to ensure that all of the various criteria used by different team members are considered, the creation of representations of design problems should be as interactive as possible. Therefore, when possible, tests should be agreed to jointly by the team before they are carried out. Furthermore, when design tools are used in a *show and tell* manner, they should be used to help explain a group's concerns, rather than to "prove" that the group's opinion is correct.

6.1.4. Getting the Most Benefit from Design Meetings

The utility of tests and other design representations in facilitating problem resolution suggests a means for improving how meetings are used by design teams. Rather than simply reporting to one another about their progress, engineers on design teams might make better use of meetings by building them around the creation of a model or test related to the problem they are addressing. As this investigation showed, a key factor in attaining the benefits of conducting tests or building models is having as much of the team participate in their development as possible. So, in place of simply reporting to one another about the problems they face, engineers might instead use a meeting to jointly create a model or develop a testing procedure that illustrates their problems. If need be, the details of the testing could be left to another time, and a follow-up meeting held to discuss the results. Shifting the focus of meetings from a passive, information dissemination process to an active, knowledge creating one might yield better engineering results and a greater sense of satisfaction in team members.

6.1.5. Use Design-Build-Test Cycles

The results of this study suggest that teams should use design-build-test cycle strategies to guide their overall development efforts. The design-build-test framework was formalized by Wheelwright and Clark (1992) based on their studies of product development practices across several industries. A single cycle is illustrated in

Figure 6.1: Wheelwright and Clark's design-build-test cycle. (Adapted from Wheelwright and Clark, 1992, p. 224.)

. As shown, the cycle begins with the recognition of a gap between a product's existing capabilities and the targets established for a new design. The design problem is framed based on this performance gap. A variety of potential solutions are then developed that may correct this shortfall, and prototypes or models (real or virtual) of each concept are built. These models are then tested, and the results used to refine both the problem statement and the solution to the problem.

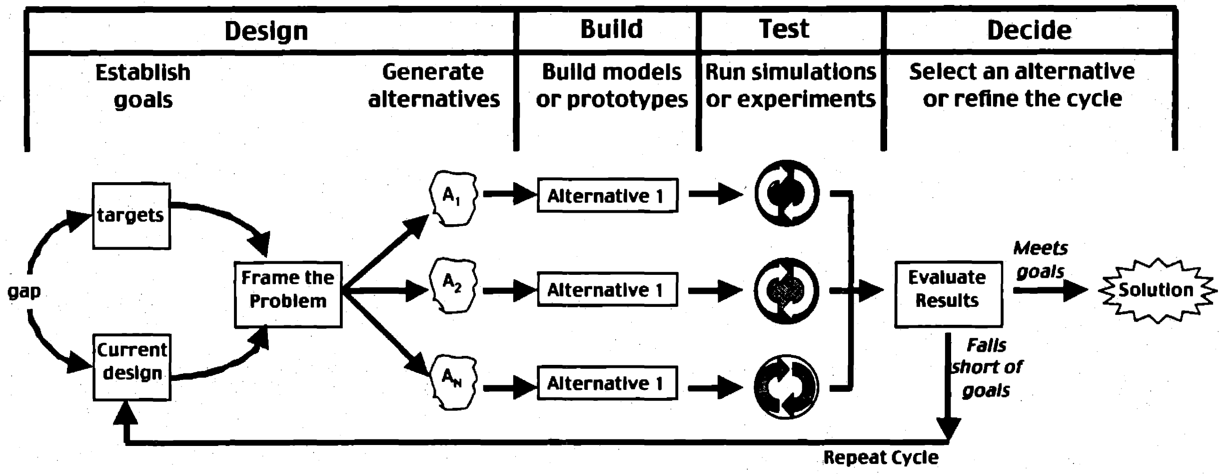

Figure 6.1: Wheelwright and Clark's design-build-test cycle. (Adapted from Wheelwright and Clark, 1992, p. 224.)

The typical argument in favor of this approach to product development is that the sequential series of tests helps to reduce the technical risk associated with the creation of the new product. This research, however, also suggests that some of the benefits associated with the design-build-test strategy may lie in its social effects. As this study has shown, tests are an effective way for design teams to resolve cross-functional problems. The design-build-test approach to development institutionalizes those benefits. Based on the results of this investigation, one would expect that teams using design-build-test approaches would be both more satisfied with the development process and produce better performing products than teams that did not use such methods.

6.1.6. Standardizing Problem Solving Methods

As discussed above, no quantitative data was collected on the benefits of standardized approaches to problem solving. However, an informal comparison between the discussions held with manufacturing personnel and those held with design engineering personnel suggests there may be benefits to having a formalized approach to solving problems. Other research studies, as described previously (see section 4.1.2), have also pointed to the benefits of such systematization.

Based on the observations made during the course of this project, several guidelines can be proposed. First, teams must be assured that the purpose of standardizing the problem solving process is not to restrict their creativity but rather to enhance it. Rather than having to "start from scratch" each time a new problem arises, the team members can arrive pre-equipped with an approach to address the problem. In order to facilitate such acceptance and "portability", however, care must be taken regarding what elements of the process are standardized. In general, the focus should be on standardizing questions, not tasks. Typically, the reverse is done: detailed methods are established, but because each problem is unique, teams are forced to modify the "standard" approach so much that they have essentially created a new process.

In this regard, a comparison can be made to the scientific method. Typically, the scientific method is described using four steps:

1. Statement of problem (What is to be studied)
2. Hypothesis about the source(s) or cause(s) of the problem
3. Design of an experiment to test the hypothesis
4. Data collection and analysis to prove or disprove the hypothesis.

Although seemingly general, this simple framework is very powerful. It can be applied nearly universally to any problem, and, in many cases, failures in experiments can be linked to failures in properly addressing one of the four steps. Honda, for example, teaches all of its employees worldwide the same problem solving approach (Nelson *et al*, 1998), and their approach is remarkably similar to the scientific method. Seven steps form the backbone of the method:

> 1. What is the plan compared to the actual situation?
> 2. What is the gap?
> 3. Conduct a gap analysis.
> 4. Define gap countermeasures.
> 5. Identify the means – money, resources, and/or people.
> 6. Who is responsible for implementing the plan?
> 7. When will it be completed? What is the schedule?
>
> (Nelson *et al*, 1998, p. 58).

In addition to the fact that the steps all seem logical and well-planned, what is more important is that all of its employees know the method, and, consequently, when they work together, understand the mental processes they are each using (Nelson et al, 1998).

Research also suggests that Toyota follows a similar strategy. Work by Sobek (1997), Nishiguchi and Beaudet (1998), and Spear (1999) indicates that Toyota trains all of its employees, both on the factory floor and in the design studios, within Toyota proper and at supplier sites, similar approaches to solving problems and designing systems. Again, the power of this approach may not lie so much in its details, as much in the fact that it facilitates communication. Furthermore, since everyone is trained in the same process, the process itself is reinforced every time engineers work together.

Clearly there are potential drawbacks to standardization. Perhaps the most notable is the potential to stifle creativity and free thinking. Based on the comments of manufacturing personnel who have used such approaches, the most effective countermeasure to such drawbacks appear to be focusing on standardizing questions, rather detailed activities, as demonstrated in Honda's approach. The goal of such formalization is not to dictate specifics, but to provide overall guidance and a common starting point that can be shared by the diverse members of a team.

6.2. Implications for Theory

The results of this research also have important implications for theories related to design team communication and knowledge sharing. Three important and interwoven concepts have been developed: individuals from different backgrounds interpret problems differently, what an individual "knows" includes standards of evaluation and methods of judgement, and the extent to which individuals participate in creating a shared evaluation system can affect their ability to effectively solve problems together.

Data from the paired interview cases collected by this study clearly illustrate that two engineers do interpret the same problem differently based on their backgrounds and previous experiences. The criteria lists also demonstrate that a key element of these different interpretations lies in the manner in which the individuals judge the benefits or drawbacks of potential solutions. Furthermore, these differences are often the result of engineers addressing related, but unique problems. Thus, the concerns of a tool designer are not the same as those of a structural engineer, and the problems about which a process engineer worries are different from those about which a design engineer worries.

The classic model of human communication based on the information processing framework, however, fails to account for such differences in meaning and evaluation. The results of this research suggest that human communication processes first consist of a search for shared meaning. This search is greatly facilitated by sharing in the creation of models, tests, or similar activities. Such practices facilitate the development of a shared understanding of a given problem by allowing individuals to point to an object or a data point rather than having to use higher level abstractions, such as words, to describe a concept or concern. Reference to such artifacts reduces the chain of abstractions required to communicate an idea, curtailing the potential for misinterpretation. Furthermore, since words include connotations of good or bad, direct reference to prototypes or models can help to remove an emotional element from problem solving processes. This reduction of emotional involvement helps individuals to focus their attention on the complexities and challenges of the problem itself, rather than on protecting their credibility or technical competence.

This research does not suggest, however, that the information processing model be thrown out. Instead, the information processing model and the abstraction-based model put forward in this study can and should exist together. The information processing model works well to explain communication processes at a relatively high level or when there are few differences between the individuals or groups that are communicating. Under these circumstances, details of meaning systems may be unimportant or the groups may already have a shared understanding of meaning. However, because of its assumption of shared meaning, the information processing model fails at the detailed, person-to-person level of human communication. At that point, a communications model that includes the need to *create* shared meanings is required to explain and improve people's relationships. The greater the differences between the individuals being studied, the more important this alternative model becomes.

6.3. Recommendations for further Research

The results of this investigation has led to as many new questions as it has answered. Several specific recommendations for additional study have been identified.

6.3.1. Improving Academia-to-Industry Research Relationships

A challenge faced by any academic study is how to collect data to support or refute the hypotheses to be studied. In investigations such as this one, the challenge is made even more difficult because the research is dependent on the cooperation and participation of companies from which to acquire data. Based on this researcher's experience, several observations and recommendations can be made to improve the effectiveness of academic-industry research consortiums, such as LAI.

At the time of this writing, LAI's data acquisition approach depended on points of contact (POCs) at each member company. When a student was ready to acquire data, he called the POCs at the companies at which he wished to work. POCs were typically associated with improvement programs at member companies and were not necessarily affiliated with product development projects themselves. Furthermore, POCs were typically mid-level managers, with no formal authority over product development projects. Therefore, when a POC received a call from a student researcher, he would simply use his own personal network to request that product development projects support the student.

Because the POC did not have any formal authority over the development projects, however, project managers could simply decline any requests to participate in a study. More than financial concerns, managers often refused to participate because of time concerns. This researcher was told by several POCs that project managers simply did not feel they could spare their engineers for even one hour to participate in a research study.

Thus, the limitations of this relationship were clearly revealed during this project. While POCs were contacted at twenty-eight sites, only nine sites actually agreed to provide data. Furthermore, while each site included numerous product development projects, typically only one to three teams would agree to participate. Although the potential existed to acquire data from a very large number of projects, such goals were never realized.

These goals were not met for lack of effort on the part of the POCs, however. In this researcher's experience, the POCs worked hard to try to provide data collection opportunities. But, because they lacked any authority over product development projects, they could not exert any pressure on teams to participate. Furthermore, the POCs' efforts were complicated by the fashion in which LAI itself operated. Since each student was responsible for establishing contact with companies, POCs would regularly receive multiple calls on the same day from students and researchers at LAI. The need to balance these multiple requests clearly complicated the task of the POCs.

Given these experiences, LAI might consider implementing several changes to improve its ability to work with member companies:

- *Establish regular contact with product development executives at member companies.* As noted above, most POCs affiliated with LAI are not associated with a particular product development project, and, because of this, can not exert any formal authority over such projects. LAI might consider enhancing the POC network by establishing regular ties to product development executives who would be in a position to mandate that their teams participate in a study. If such executive-level connections were established, they might be maintained either at the focus team leader- or research council-level, rather than with individual students[5].
- *Have focus team leaders to make contact with POCs for all students on a focus team.* This approach would continue to keep the company-to-researcher contact at a low level, while still reducing the number of calls a POC is likely to receive. In addition, consolidating such calls would enhance a focus team leader's ability to coordinate the research efforts within her or his team. This enhanced coordination could facilitate several students gathering data on a single visit, reducing the burden to member companies.
- *Consolidate all communication with companies with the LAI research council.* Rather than having students or focus team leaders contact companies, researchers could instead place requests with the research council. Members of the council could then consolidate and coordinate attempts to gather data at LAI companies. Research council members could be "assigned" to a small group of companies, allowing them to build relationships with company representatives and improving their ability to locate specific projects that would make a good match with a given study.

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[5] At the time of this writing, LAI researchers were grouped into focus teams. These teams oversaw and implemented the day-to-day research tasks of the consortium. Academic oversight was then provided by the LAI research council, which was composed of the MIT faculty members associated with LAI.

LAI represents a unique partnership between industry, academia, and government and has already made significant contributions to the aerospace industry. Furthermore, the personal networks that it has created between these three communities are invaluable. Improvements in the researcher-to-company relationship would only enhance the ability of researchers to collect meaningful data, which in turn would increase the benefits industry receives through its affiliation with LAI.

6.3.2. Establishing Connections between Problem Interpretations and Performance

The criteria list data collected for this study proved useful in demonstrating that engineers do interpret problems differently. These lists, however, did not provide an indication of how such differences affected problem solving performance. Two recommendations for improving this method are:

1) Replace the subjective outcome measures used in this investigation with quantitative ones (such as number of engineering changes to a design or comparisons of product performance between two teams developing the same product).

2) Ask interviewees to provide what they believe to be the criteria list of the other individual interviewed for the case. The accuracy of these lists might show a stronger correlation with outcome performance.

6.3.3. Collect Data on Changes in Criteria over Time

Another potential improvement to the criteria-list method developed during this study would be to sample product developers' lists over time while they were actively engaged in solving a problem. Rather than asking engineers to recall a problem they had solved in the past, a researcher might instead first ask an engineer to describe a problem he is currently solving. Then, the engineer could be asked to provide his criteria list for the problem. Using a web-, phone-, or mail-based survey, the researcher could then ask the engineer to provide the list on later occasions. When changes are observed, the engineer could be interviewed in detail again, in an attempt to ascertain what happened that changed his criteria list (such as a test, for example).

Furthermore, the criteria lists could also form a method for tracking and evaluating learning over time. A researcher might attempt a long term study, for example, in which she tracked engineers over multiple projects. By comparing criteria lists from one project to another when similar problems arise, the researcher might be able to demonstrate whether or not an engineer had learned from his past experiences. Such learning might be captured when an engineer adds a criterion to his list that had not been present during a prior, similar problem solving effort. If the engineer added the criterion because of his previous experience, it might help to quantify his learning. Further comparisons between engineers and projects might then be able to highlight practices that facilitate learning.

6.3.4. Effects of Design-Build-Test Strategies

The results of this study indicate that the effectiveness of design-build-test product development strategies may arise in part from the social benefits of emphasizing testing. Future studies might investigate this hypothesis directly by comparing teams developing similar products but emphasizing testing to different degrees. Study participants should be asked to rate their personal satisfaction with the development process used by their team. Such data, when analyzed in combination with product performance outcomes, could yield a variety of interesting insights.

6.3.5. Benefits of Standardizing Problem Solving Processes

Several issues related to the standardization of problem solving processes were raised during the course of this investigation. The first question worthy of further study suggested by this project is to assess whether or not teams that use standardized problem solving processes are more effective than teams without formalized methods. A second issue to be addressed is the effect on performance of varying levels or standardization: do teams that use a standardized list of questions perform better than teams that use a standardized list of tasks? Finally, engineers could be asked to rate the amount of creativity they felt their problem solving processes allowed, and the responses of individuals who used standardized methods compared to those who did not.

6.4. Limitations of this Study

While this study has provided useful insights into problem solving on product development teams, it does have several limitations. Perhaps the most important is that it used an approach requiring engineers to describe their past experiences. Participants, however, may have already spent considerable time rationalizing these experiences, biasing their recollections of the events. In addition, the participants may not have recalled the events which they described with total accuracy, not because deliberate intent, but simply from forgetfulness. While participants were asked to rate the quality of their memory, there are no complete assurances that they did not remember the events incorrectly, even if they thought they remembered them well.

Another limitation of this study is that it relied on a single informant for the majority of the cases studied. Thus, significant details about a case may have been omitted or skewed by obtaining just one person's description. Although this study attempted to achieve a fairly large dataset to compensate for this weakness, in addition to several cases for which paired data was acquired, there was still the potential for biases. Future studies may endeavor to overcome such shortcomings, perhaps using some of the suggestions made above, in an effort to either lend additional support for the conclusions of this study or to refute them.

6.5. Final Thoughts: A Social Perspective on Integration

Earlier, it was argued that integration was, at least in part, a social process. Because of the complexity of their environments and the tasks that they must accomplish, product development organizations tended to evolve into collections of highly specialized, and highly skilled, subgroups. Delivering a successful product, however, required that the knowledge possessed by these different groups be combined – that their knowledge be integrated.

This study has demonstrated that a consequence of differentiation within organizations was that individuals from different groups tended to interpret design problems differently. Furthermore, successfully resolving these problems required that the individuals create a shared evaluation system with which to judge the benefits or drawbacks of potential solutions. The creation of such an evaluation system, then, can be considered a first step in the integration process. Without such a system, disputes on design teams tended to fester unresolved. Once such a shared method of judging solutions was in place, on the other hand, teams were able to solve their problems and continue their development efforts.

As was argued, the creation of this shared evaluation system was primarily a social process. It required that product developers with different backgrounds interact and exchange ideas so that they could explain to one another what they each considered to be important. The way in which design tools were used played a critical role during such social interactions, facilitating or inhibiting teams' abilities to develop shared understandings of the problems which they faced. Thus, the integration process was seen to be as much a social phenomenon as a technological one, and by facilitating the human processes of communication, successful design teams facilitated the technological integration of the products which they developed.

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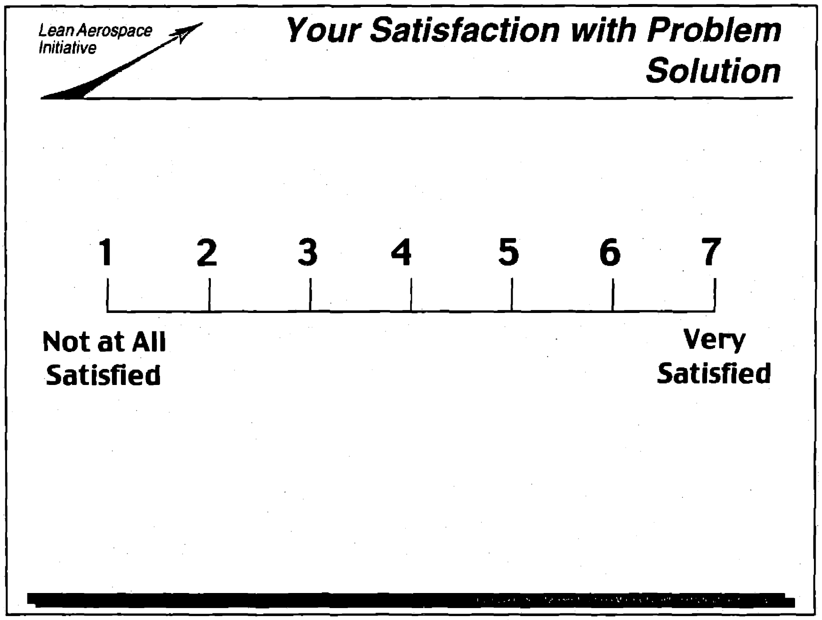
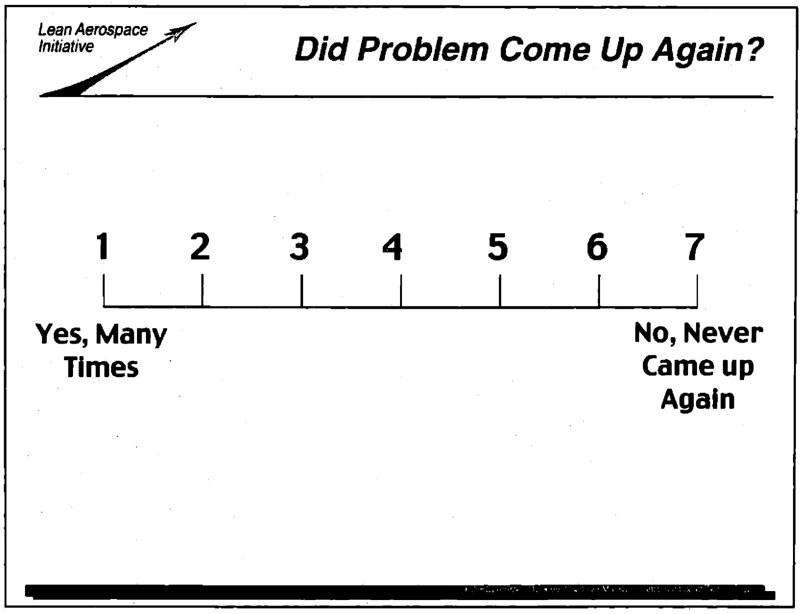
APPENDIX A: ANSWER SCALES USED DURING INTERVIEWS

Illustrated below are the answer scales used during the interviews for this research.



Lean Aerospace Initiative

Your Satisfaction with Problem Solution



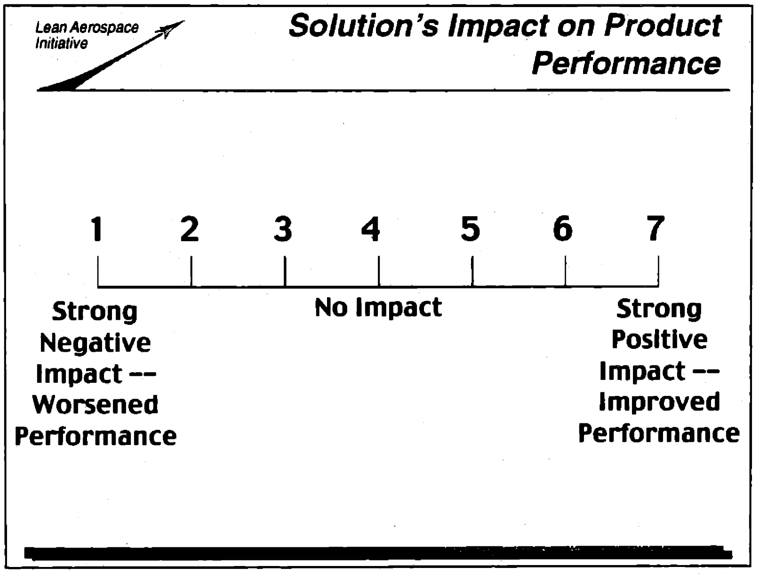
Lean Aerospace Initiative

Did Problem Come Up Again?

1 2 3 4 5 6 7

Yes, Many Times

No, Never Came up Again



Lean Aerospace Initiative

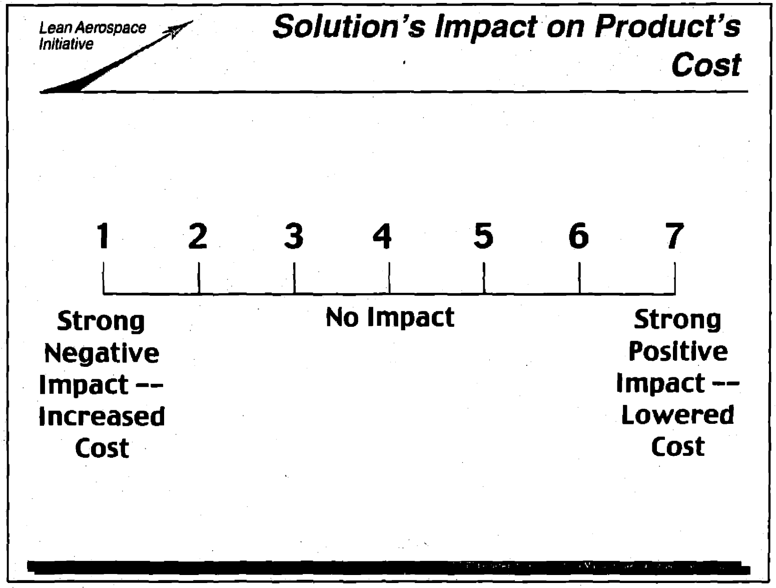
Solution's Impact on Product Performance

1 2 3 4 5 6 7

Strong Negative Impact -- Worsened Performance

No Impact

Strong Positive Impact -- Improved Performance



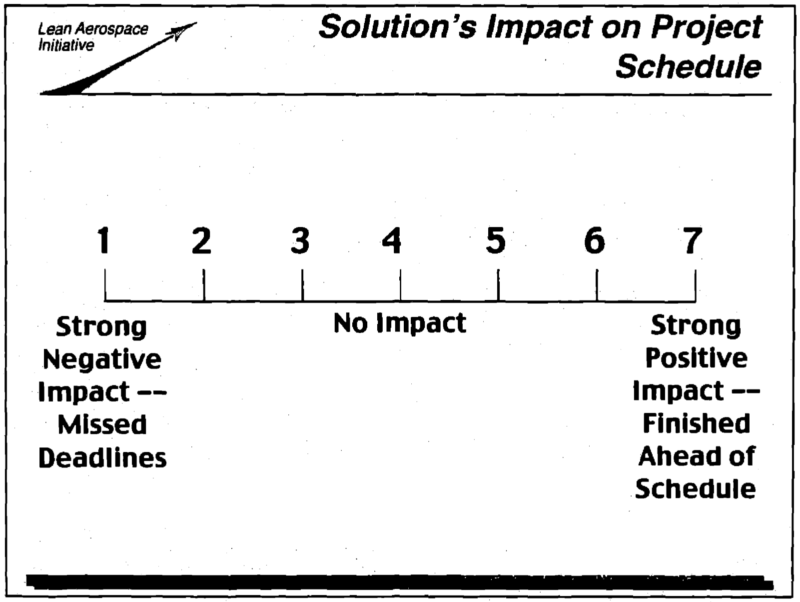
Lean Aerospace Initiative

Solution's Impact on Product's Cost

Strong Negative Impact -- Increased Cost

No Impact

Strong Positive Impact -- Lowered Cost



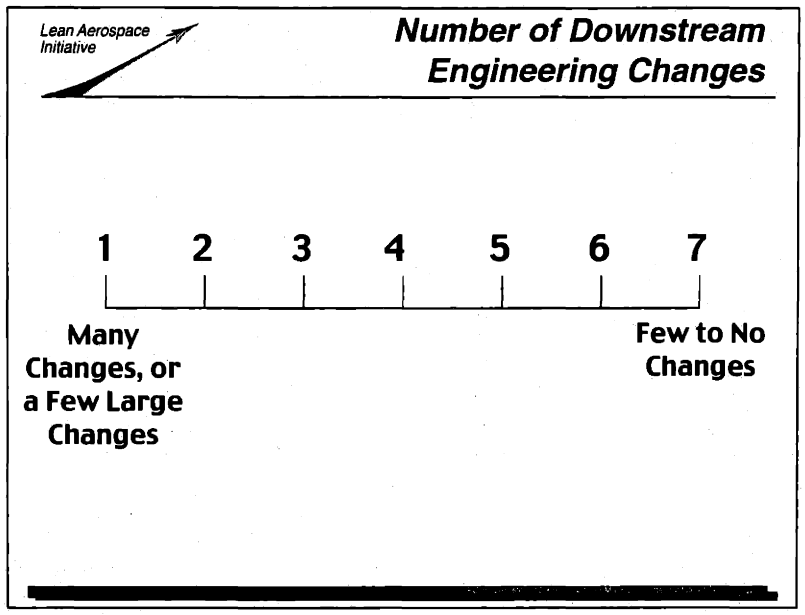
Lean Aerospace Initiative

Solution's Impact on Project Schedule

Strong Negative Impact -- Missed Deadlines

No Impact

Strong Positive Impact -- Finished Ahead of Schedule



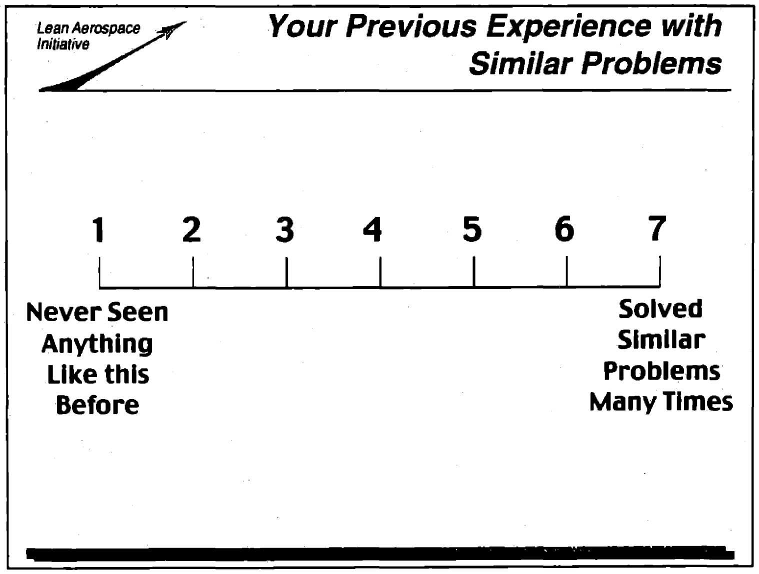
Lean Aerospace Initiative

Number of Downstream Engineering Changes

1 2 3 4 5 6 7

Many Changes, or a Few Large Changes

Few to No Changes



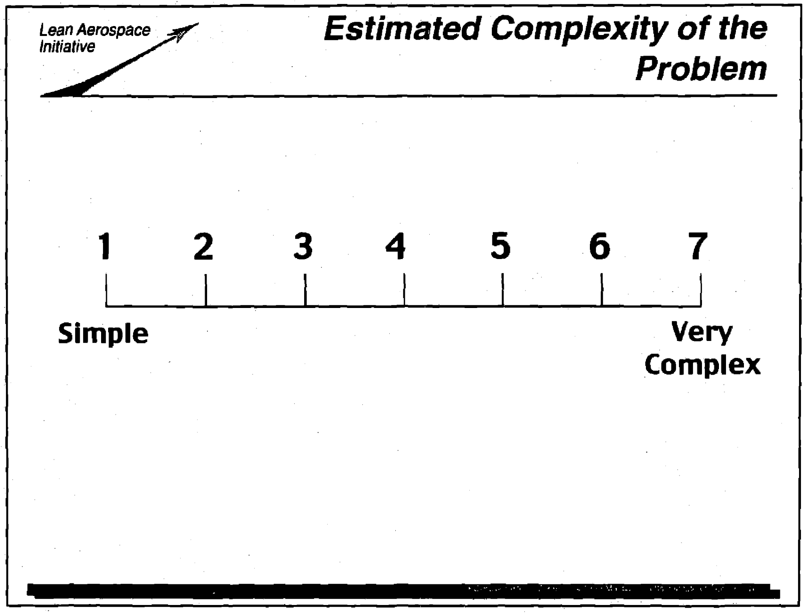
Lean Aerospace Initiative

Your Previous Experience with Similar Problems

1 2 3 4 5 6 7

Never Seen Anything Like this Before

Solved Similar Problems Many Times



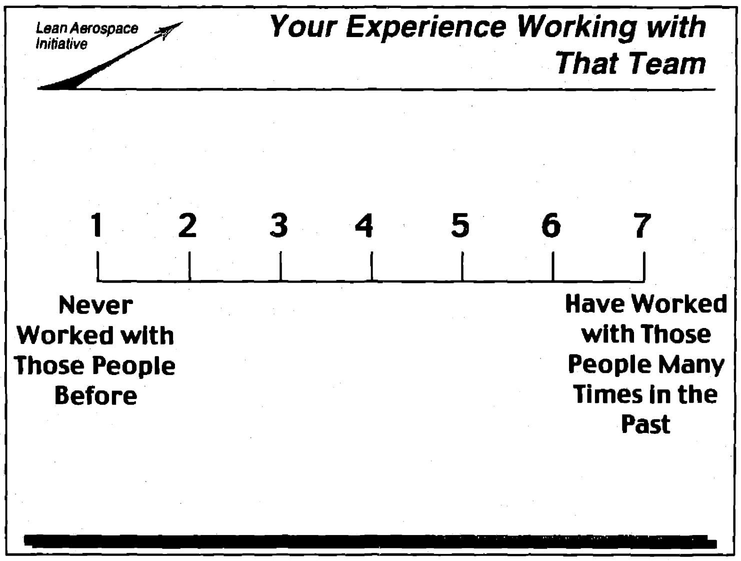
Lean Aerospace
Initiative

Estimated Complexity of the Problem

1 2 3 4 5 6 7

Simple

Very
Complex



Lean Aerospace
Initiative

Your Experience Working with That Team

1 2 3 4 5 6 7

Never
Worked with
Those People
Before

Have Worked
with Those
People Many
Times in the
Past

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Accuracy of Memory

1 2 3 4 5 6 7

Do Not Remember this Case Very Well

Do Remember this Case Very Well

APPENDIX B: FACTOR CITATION DATA FOR PAIRED AND INDIVIDUAL INTERVIEW CASES

Abbreviations

Following is a list of the abbreviations used in the tables.

For all factors (e.g., management intervention, use of tests, social problems, etc.) a "1" indicates that the factor was cited by the interviewee and a "0" indicates that it was not cited.

A value of "99" indicates missing data or no response supplied by interviewee.

Value meanings are provided below for all other data in the table.

ID
Case identification number

BTWN
What groups were involved in the dispute. Values indicate:
1: Engineering group v. Another Engineering Group
2: Factions within an Engineering Group
3: Engineering vs. Manufacturing/Industrial Engineering
4: Engineering vs. Supplier
5: Engineering vs. Customer
6: Manufacturing/Industrial Engineering vs. Factory Line Operators
7: Manufacturing/Industrial Engineering vs. Supplier

PHASE
Development phase during which dispute occurred. Values indicate:
1: Conceptual Design
2: Preliminary Design
3: Detail Design
4: Product Improvement, Engineering-Manufacturing Development (EMD), or Prototype Testing
5: Mass Production

DIFF
Difficulty level of case as reported by interviewee. Values indicate:
1: Easy
2: Difficult
99: Difficulty level not specified

MGMT
Management intervention.

CRIT_MEM
Critical team member.

ENG_EXP
Reliance on engineering expertise.

TRADE
Use of trade studies.

ST
Show and tell.

TEST
Use of tests.

TIME
Time pressure

COLOC
Co-located team.

MTGS
Frequent face-to-face meetings.

OBJ
Shared objectives or well understood requirements.

WIN_WIN
Development of a win-win solution

REAS_WHY
Delineation of technical issues/"reasons why"

SOCPROB
Social problems.

BAD_BO
Misuse of boundary objects or test data.

BAD_MET
Poorly defined or understood requirements or lack of shared metrics.

BAD_COM
Unclear or split lines of communication and/or authority.

ALT
How design alternatives were considered. For individual interview cases, values indicate:
1: Serial or iterative development of a single design concept.
2: Parallel development of two design concepts.
3: Parallel development of three or more design concepts.
For paired interview cases, the values indicate:
1: Both said iterative/serial development
2: One said iterative/serial, the other said two in parallel
3: One said iterative/serial, the other said three or more in parallel.
4: Both said two in parallel
5: One said two in parallel, the other said three in parallel
6: Both said three in parallel.

SAT
Satisfaction with solution. For individual cases, values range from 1 (not satisfied) to 7 (very satisfied). For paired interview cases, values are the average of a pair's responses.

PERF
Solution's impact on the product's performance (1 = worsened performance to 7 = improved performance). For paired cases, value indicates the average of a pair's response.

COST
Solution's impact on the product's cost (1 = increased cost to 7 = reduced cost). For paired cases, value indicates the average of a pair's response.

SCH
Solution's impact on the project's schedule (1 = missed deadlines to 7 = finished ahead of schedule). For paired cases, value indicates the average of a pair's response.

EXP
Interviewee's previous experience solving similar problems (1 = never solved similar problem before to 7 = solved similar problems many times). For paired cases, value indicates the average of a pair's response.

COMPL
Interviewee's estimate of the problem's complexity, including both social and technical factors (1 = simple to 7 = very complex). For paired cases, value indicates the average of a pair's response.

TEAM
Interviewee's past experience working with the other members of the team (1 = never worked with the other team members before to 7 = worked with them many times in the past).

MEM
Interviewee's rating of his/her memory of the details of the case (1 = did not remember case well to 7 = remembered case very well). For paired cases, value indicates the average of a pair's response.

Individual Interview Case Data

ID	BTWN	PHASE	DIFF	MGMT	CRIT_MEM	ENG_EXP	TRADE
1	1	1	2	1	1	0	0
2	4	1	1	0	0	0	0
3	1	1	2	0	0	0	0
4	4	1	1	0	1	0	0
5	2	4	1	0	0	1	0
6	1	4	2	0	0	0	0
7	2	4	2	1	0	0	0
8	3	4	2	0	0	0	0
9	2	4	2	0	0	0	0
10	3	2	1	0	0	1	0
11	1	2	2	0	0	0	0
12	2	4	1	0	0	1	0
13	1	3	1	0	0	0	0
14	1	3	2	0	0	0	1
15	4	3	1	0	0	0	0
19	5	1	1	0	0	1	0
20	1	1	2	1	0	0	1
21	2	4	1	0	0	0	0
22	5	4	2	0	0	0	0
23	2	4	2	0	0	0	0
24	1	4	1	0	0	0	0
25	1	4	1	0	1	0	0
26	1	4	2	0	0	0	0
27	2	4	2	0	0	0	0
28	4	4	1	0	0	0	0
29	3	4	99	0	1	0	0
30	3	4	2	0	0	1	0
31	3	4	1	0	0	1	0
32	3	4	1	1	0	0	0
33	2	1	99	0	0	0	1
34	4	1	2	0	0	0	1
35	4	1	99	1	0	0	1
36	4	1	2	1	0	0	0
37	1	1	2	0	0	0	0
38	4	5	99	1	0	0	0
39	1	3	2	0	1	1	0
40	3	5	1	0	1	0	0
41	2	5	99	0	0	0	0
42	2	2	99	1	0	1	0
43	2	1	1	0	1	0	0
44	4	3	2	0	0	0	1
45	4	1	99	0	0	0	0
46	3	4	99	0	0	0	0
47	3	5	99	0	0	0	0
48	3	5	99	0	0	0	0
49	6	5	1	0	0	0	0
50	6	5	2	0	0	0	0
51	6	5	1	0	1	0	0
52	6	5	2	0	0	0	0
53	6	5	1	0	0	0	0
54	6	5	2	0	0	0	0
55	6	5	1	0	0	0	0

ID	BTWN	PHASE	DIFF	MGMT	CRIT_MEM	ENG_EXP	TRADE
56	6	5	2	0	0	0	0
57	6	5	1	0	0	0	0
58	6	5	2	0	0	0	0
59	6	5	2	0	0	1	0
60	6	5	2	0	0	0	0
61	6	4	1	0	0	0	0
62	6	4	2	0	0	0	0
63	3	4	2	1	0	0	0
64	7	5	2	0	0	0	0
65	3	4	1	0	0	0	0
66	3	5	99	0	1	0	0
67	3	5	99	0	0	0	0
68	3	5	99	0	0	0	0
69	2	2	99	0	0	1	0
70	3	5	99	0	0	0	0
71	1	3	99	1	0	0	0
72	3	3	99	0	0	0	0
73	5	4	99	1	0	1	0
74	2	3	99	0	0	0	0
75	3	5	99	1	1	0	0
76	5	3	99	1	0	0	0
77	2	4	99	0	0	0	0
78	2	99	99	1	0	0	0
79	2	99	99	1	0	0	0
80	1	4	99	0	1	0	0
81	1	4	2	0	0	0	1
82	1	99	1	0	0	0	0
83	2	99	2	0	0	0	0
84	1	99	1	0	0	0	0
85	6	99	2	1	0	0	0
86	2	99	1	0	0	0	0
87	1	99	2	0	0	0	0
88	2	99	1	0	0	0	0
89	1	5	99	1	0	0	0
90	7	5	1	1	1	0	0
91	6	5	99	0	0	0	0
92	2	4	1	0	0	0	0
93	6	99	2	0	0	0	0
94	2	3	1	0	0	0	0
95	3	5	2	0	0	0	0
96	4	4	2	1	0	0	0
97	4	3	1	0	0	0	0
98	1	5	1	0	0	0	0
99	4	4	2	1	1	0	0
100	1	4	2	1	0	0	1
101	3	5	1	0	0	0	0

ID	ST	TEST	TIME	COLOC	MTGS	OBJ
1	1	0	0	0	0	1
2	0	0	0	0	0	0
3	0	0	0	0	1	0
4	1	0	0	0	1	0
5	0	1	0	0	0	0
6	1	0	0	0	0	0
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9	1	1	0	0	0	0
10	1	0	0	0	0	0
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44	0	1	0	0	0	1
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46	1	1	0	1	0	0
47	0	1	0	1	0	0
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52	1	1	0	1	0	0
53	1	0	0	1	0	0
54	0	1	0	1	0	0
55	1	1	0	1	0	0

ID	ST	TEST	TIME	COLOC	MTGS	OBJ
56	0	1	0	1	0	0
57	0	1	0	1	0	0
58	1	0	0	0	1	0
59	0	1	1	0	0	0
60	1	1	0	0	0	0
61	1	1	0	0	0	1
62	1	0	0	0	1	0
63	1	1	0	0	0	0
64	0	1	0	0	0	0
65	0	1	0	0	0	1
66	1	1	0	0	1	1
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94	1	0	0	0	1	0
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99	0	0	0	0	1	0
100	1	0	1	0	0	0
101	1	1	0	0	0	0

ID	WIN_WIN	REAS_WHY	SOCPROB	BAD_BO	BAD_MET	BAD_COM
1	0	0	1	0	0	0
2	1	0	0	0	0	0
3	0	0	0	1	0	1
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	1	0
7	0	0	0	0	1	0
8	0	0	1	0	0	0
9	0	0	1	0	0	0
10	0	0	0	0	0	0
11	0	1	0	0	0	0
12	0	0	0	0	0	0
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14	0	0	0	1	1	0
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19	0	0	0	0	0	0
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ID	WIN_WIN	REAS_WHY	SOCPROB	BAD_BO	BAD_MET	BAD_COM
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60	0	0	0	0	0	0
61	0	0	0	0	0	0
62	0	0	1	0	0	0
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99	0	0	0	0	0	0
100	0	0	0	0	0	1
101	0	0	0	1	0	0

ID	ALT	SAT	PERF	COST	SCH	EXP
1	2	6	6	4	4	7
2	1	6	3	3	2	2
3	1	6	6	4	2	6
4	1	6	7	4	5	6
5	1	7	7	4	4	6
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8	2	7	7	4	4	7
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27	3	5	6	2	3	2
28	3	6	4	5	4	5
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31	2	7	3	6	5	1
32	1	6	6	6	5	7
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39	1	4	4	3	4	2
40	3	6	6	2	4	2
41	1	6	6	4	6	5
42	2	6	3	3	5	6
43	1	6	6	99	99	1
44	3	7	5	6	6	6
45	1	99	99	99	99	3
46	3	6	6	7	4	4
47	1	7	6	4	4	7
48	1	7	7	7	4	4
49	1	5	6	5	5	6
50	1	6	5	7	6	2
51	1	6	7	6	6	3
52	3	7	5	6	6	2
53	1	5	6	6	7	5
54	1	5	7	7	7	6
55	1	7	7	5	7	7

ID	ALT	SAT	PERF	COST	SCH	EXP
56	1	4	6	6	4	4
57	1	7	7	4	5	6
58	1	5	6	5	5	3
59	1	6	5	5	6	6
60	1	4	5	5	5	4
61	3	7	6	7	7	1
62	1	4	4	4	4	7
63	1	4	6	6	7	7
64	1	4	5	6	6	6
65	1	7	6	6	6	4
66	1	5	5	6	6	5
67	1	5	7	6	5	3
68	3	7	6	6	6	7
69	1	6	6	5	1	2
70	3	5	6	4	4	2
71	1	6	4	6	2	7
72	3	6	3	5	4	7
73	3	6	5	4	3	7
74	2	5	6	4	4	4
75	3	99	5	4	3	2
76	2	2	4	4	3	5
77	2	6	2	4	5	6
78	2	1	2	2	3	6
79	2	5	4	3	3	4
80	2	4	6	3	3	6
81	3	5	4	4	4	6
82	1	7	6	6	6	6
83	1	7	4	4	4	1
84	3	6	5	5	4	3
85	3	6	6	2	2	4
86	3	6	6	3	6	3
87	2	5	4	1	1	1
88	99	7	6	5	5	1
89	3	6	6	6	7	1
90	3	6	7	5	3	2
91	99	6	7	7	4	1
92	2	6	6	6	5	5
93	1	6	7	5	4	2
94	2	7	4	4	4	7
95	99	6	5	6	6	4
96	99	3	4	4	1	5
97	1	5	3	5	6	6
98	99	7	4	3	3	5
99	3	7	4	4	3	1
100	3	3	5	99	1	3
101	3	6	3	4	3	6

ID	COMPL	TEAM	MEM
1	5	2	99
2	5	2	99
3	6	2	99
4	6	6	99
5	4	4	99
6	6	4	99
7	2	1	99
8	5	1	99
9	5	5	99
10	1	6	99
11	4	1	99
12	5	3	99
13	4	3	6
14	6	5	5
15	5	6	6
19	5	3	6
20	6	1	6
21	4	1	7
22	7	1	7
23	5	6	5
24	7	7	6
25	6	5	7
26	7	3	7
27	6	4	7
28	2	5	5
29	6	3	6
30	5	1	7
31	7	1	7
32	6	7	6
33	6	2	6
34	7	1	7
35	5	7	7
36	6	1	6
37	4	7	6
38	6	4	7
39	6	2	5
40	5	3	6
41	2	4	7
42	6	6	7
43	7	6	7
44	6	6	7
45	7	5	7
46	6	7	6
47	2	7	6
48	2	1	7
49	6	6	99
50	6	1	99
51	6	5	99
52	5	6	99
53	5	3	99
54	5	3	99
55	6	7	99

ID	COMPL	TEAM	MEM
56	6	6	99
57	3	6	99
58	6	1	99
59	4	5	99
60	4	4	99
61	5	2	6
62	7	6	6
63	7	6	7
64	7	4	7
65	3	3	7
66	6	5	5
67	3	6	6
68	6	5	6
69	6	7	7
70	6	1	6
71	4	6	5
72	6	6	7
73	3	3	5
74	7	4	7
75	6	5	6
76	6	4	4
77	5	4	7
78	3	2	6
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80	5	4	5
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83	5	4	7
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87	7	1	5
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89	6	1	5
90	7	4	7
91	6	3	6
92	2	6	6
93	7	3	7
94	5	1	7
95	6	1	7
96	5	4	7
97	4	2	7
98	4	6	7
99	5	2	5
100	5	2	6
101	3	2	6

Paired Interview Case Data

ID	BTWN	PHASE	MGMT	CRIT_MEM	ENG_EXP	TRADE	ST
7	2	4	1	0	0	0	0
20	1	1	1	0	0	2	0
33	2	1	0	0	0	2	0
34	4	1	0	0	0	2	0
40	3	5	0	2	0	0	1
43	2	1	0	1	0	0	2
66	3	5	0	2	0	0	2
67	3	5	0	0	0	0	2
68	3	5	0	0	0	0	1
69	2	2	0	1	1	0	1
70	3	5	0	1	0	0	1
73	5	4	1	0	1	0	1
76	5	3	1	0	1	0	1
77	2	4	0	0	0	0	2
80	1	4	1	1	0	0	0
82	1	99	0	0	0	0	2
83	2	99	0	0	0	0	2
86	2	99	0	0	0	0	1
87	1	99	0	0	0	0	0
88	2	99	0	0	0	0	0
98	1	5	0	0	0	0	2
100	1	4	1	0	0	1	2
101	3	5	0	0	0	0	2
102	1	3	0	0	0	2	2
103	1	4	0	2	0	0	2
104	1	4	0	0	0	0	0

ID	TEST	TIME	COLOC	MTGS	OBJ	WIN_WIN
7	0	0	0	1	0	0
20	2	0	0	0	2	0
33	2	0	0	0	2	0
34	2	0	0	0	0	0
40	1	2	1	1	0	0
43	0	1	1	1	0	0
66	2	0	0	2	2	0
67	2	0	0	0	0	0
68	2	0	0	1	0	0
69	2	2	0	0	0	0
70	1	0	0	1	0	0
73	2	0	0	1	0	0
76	2	0	0	0	0	0
77	0	0	0	2	1	0
80	2	1	0	0	1	0
82	2	0	1	1	1	0
83	0	0	1	1	2	0
86	0	0	0	2	1	0
87	2	0	0	2	0	0
88	2	0	0	2	2	0
98	0	0	0	0	0	0
100	0	2	0	1	0	0
101	2	0	0	1	0	0
102	0	0	0	1	1	0
103	2	0	0	0	0	0
104	2	0	0	0	0	0

ID	REAS_WHY	SOCPROB	BAD_BO	BAD_MET	BAD_COM	ALT
7	0	0	0	2	1	2
20	0	0	0	0	0	6
33	0	1	0	0	0	6
34	0	0	0	0	0	6
40	1	1	0	0	1	3
43	1	0	0	0	0	3
66	0	2	0	0	0	3
67	0	1	0	0	0	3
68	0	0	0	0	0	5
69	0	0	1	0	0	3
70	0	0	0	0	0	6
73	0	0	0	1	0	6
76	0	0	1	0	0	4
77	0	1	0	0	0	4
80	0	0	0	0	0	5
82	0	0	0	0	0	1
83	0	0	0	1	0	2
86	1	0	0	0	0	3
87	0	2	0	0	1	2
88	0	0	0	0	0	99
98	0	0	0	0	1	99
100	0	0	0	0	2	6
101	0	0	1	0	0	6
102	0	0	0	1	0	5
103	0	0	0	0	0	1
104	0	1	0	0	0	6

ID	SAT	PERF	COST	SCH	EXP	COMPL
7	3.5	3.5	3	3	5	2.5
20	5.5	5.0	6	99	6	6.5
33	5.5	5.5	5	4	5	6.0
34	6.5	5.0	6	6	5	7.0
40	5.5	6.0	4	5	4	5.0
43	6.0	6.0	99	99	3	6.5
66	5.5	6.0	7	7	4	5.5
67	4.5	7.0	5	4	5	3.0
68	7.0	5.0	5	5	7	4.5
69	5.5	5.0	4	2	2	6.0
70	5.5	4.5	4	4	4	4.0
73	5.0	4.0	3	3	6	4.5
76	4.0	5.0	4	4	6	6.0
77	6.0	4.0	5	6	6	4.0
80	3.0	4.5	3	4	6	5.0
82	7.0	6.0	6	6	7	3.0
83	6.0	4.0	4	4	1	5.5
86	6.0	6.0	5	5	5	5.5
87	3.5	3.0	2	1	3	7.0
88	7.0	4.0	6	5	3	3.5
98	6.5	4.0	3	3	6	5.0
100	4.0	5.0	99	2	3	5.0
101	6.5	4.5	6	99	7	2.0
102	6.0	5.0	5	5	6	3.5
103	6.0	4.5	99	5	6	3.0
104	5.0	4.5	99	3	3	6.0

ID	TEAM	MEM	UNIQCRIT	UNIQPROB
7	2.5	99	99.00	99.00
20	2.0	6	99.00	99.00
33	3.0	6	99.00	99.00
34	3.5	6	99.00	99.00
40	3.0	6	99.00	99.00
43	3.5	6	99.00	99.00
66	6.0	6	.56	.50
67	6.5	6	.50	.50
68	4.5	6	.60	.75
69	5.0	7	.33	.00
70	3.5	6	.50	.00
73	4.0	5	.25	.00
76	5.0	6	99.00	99.00
77	4.5	7	.20	.00
80	4.5	5	1.00	.50
82	6.5	7	.43	.00
83	3.0	6	.71	.00
86	2.5	6	1.00	.00
87	3.0	6	.20	.50
88	5.0	7	1.00	1.00
98	6.0	7	.50	.67
100	1.5	6	.56	.00
101	4.0	7	.14	.00
102	4.5	6	.50	.50
103	4.8	99	.50	.67
104	5.5	99	1.00	.50

APPENDIX C: CRITERIA LISTS FOR PAIRED INTERVIEW CASES

Following are the criteria lists for all paired interview cases. The criteria are listed in the order in which they were described by the interviewees, and no special significance should be attributed to their sequence. In most instances, criteria are cited as direct quotes from the interviewees. However, in order to ensure confidentiality and protect proprietary information, some terminology has been altered.

Arrows between criteria indicate that they are shared by both interviewees. Numbers in parentheses after each criterion indicate which problem the criterion is addressing, and problem labels are provided below the criteria list for each case.

Case ID Number: 66
Problem Description: Aircraft fuselage access door failing to fit properly

Criteria Lists:

Engineering Lead	Tooling Lead
Door fit (1)	Control door trim (1)
Door stiffness (1)	Control hinge location (1)
Minimize door size (1)	Door fit (1)
Ensure door interchangeability (1)	
Allow for bigger gaps (1)	
Eliminate operator error (2)	

Total Number of Criteria: 9
Number of Unique Criteria: 7
Unique Criteria Ratio: 0.78

Problems:
(1) Door fit and design
Manufacturing process
(2) design

Total Number of Problems: 2
Number of Unique Problems: 1
Unique Problem Ratio: 0.50

Case ID Number: 67

Problem Description: Aircraft component manufacturing quality problem associated with tooling error

Criteria Lists:

Design Engineer	Tooling Engineer
Part fit (1)	Avoid past mistakes (1)
	Tool performance (1)
	Avoid adding process steps (2)

Total Number of Criteria: 4
Number of Unique Criteria: 2
Unique Criteria Ratio: 0.50

Problems:

(1) Part fit and tool performance
(2) Impact to manufacturing process flow

Total Number of Problems: 2
Number of Unique Problems: 1
Unique Problem Ratio: 0.50

Case ID Number: 68

Problem Description: Failure of a reaming process to meet hole diameter tolerances for an aircraft component

Criteria Lists:

Process Engineer	Design Engineer
Meet part acceptance criteria (1)	Do not invalidate fatigue article test data (2)
	Ensure worst case part still meets acceptance criteria (1)
	Do not impact aircraft aerodynamics (3)
	Do not affect part interchangeability (4)

Total Number of Criteria: 5
Number of Unique Criteria: 3
Unique Criteria Ratio: 0.60

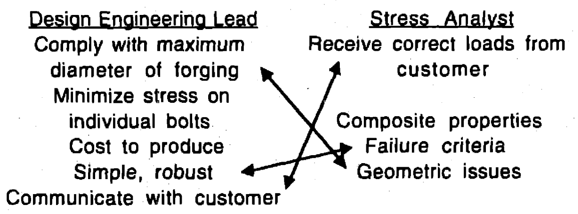
Problems:

(1) Ensure part meets acceptance criteria
(2) Maintain validity of fatigue test data
(3) Avoid changes to aircraft aerodynamics
(4) Part interchangeability

Total Number of Problems: 4
Number of Unique Problems: 3
Unique Problem Ratio: 0.75

Case ID Number: 69
Problem Description: Design of a rocket engine support structure

Criteria Lists:



Design Engineering Lead	Stress Analyst
Comply with maximum diameter of forging	Receive correct loads from customer
Minimize stress on individual bolts	Composite properties
Cost to produce	Failure criteria
Simple, robust	Geometric issues
Communicate with customer	

Total Number of Criteria: 9
Number of Unique Criteria: 3
Unique Criteria Ratio: 0.33

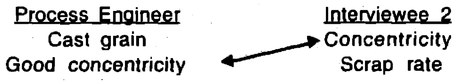
Problems:

(1) Design of support structure

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 70
Problem Description: Problems with quality of a rocket engine starter cartridge

Criteria Lists:



Process Engineer	Interviewee 2
Cast grain	Concentricity
Good concentricity	Scrap rate

Total Number of Criteria: 4
Number of Unique Criteria: 2
Unique Criteria Ratio: 0.50

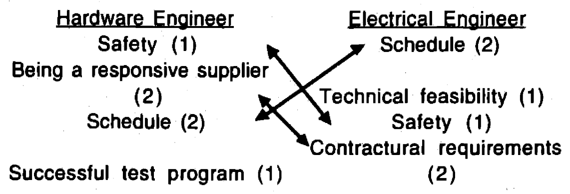
Problems:

(1) Manufactured quality of starter cartridge

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 73
Problem Description: Design an aircraft power system control unit

Criteria Lists:



Hardware Engineer	Electrical Engineer
Safety (1)	Schedule (2)
Being a responsive supplier (2)	Technical feasibility (1)
Schedule (2)	Safety (1)
	Contractural requirements (2)
Successful test program (1)	

Total Number of Criteria: 8
Number of Unique Criteria: 2
Unique Criteria Ratio: 0.25

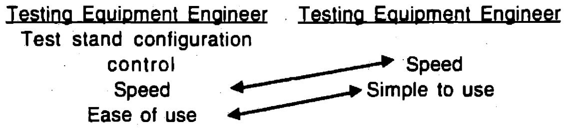
Problems:

(1) Control unit design
(2) Customer relations

Total Number of Problems: 2
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 77
Problem Description: Design of an automated test stand for testing aircraft power distribution control units

Criteria Lists:



Testing Equipment Engineer	Testing Equipment Engineer
Test stand configuration control	Speed
Speed	Simple to use
Ease of use	

Total Number of Criteria: 5
Number of Unique Criteria: 1
Unique Criteria Ratio: 0.20

Problems:

(1) Test stand design

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 80

Problem Description: Design of an aircraft subsystem control board

Criteria Lists:

Software Engineer	Hardware Engineer
Better hardware performance (1)	Risk (1)
Support object-oriented development method (2)	Commonality (1)
	Time (1)

Total Number of Criteria: 5
Number of Unique Criteria: 5
Unique Criteria Ratio: 1.00

Problems:

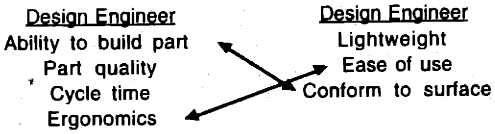
(1) Control board design
(2) Implementing object-oriented methods

Total Number of Problems: 2
Number of Unique Problems: 1
Unique Problem Ratio: 0.50

Case ID Number: 82

Problem Description: Design of a drill for aircraft component manufacturing

Criteria Lists:



Design Engineer	Design Engineer
Ability to build part	Lightweight
Part quality	Ease of use
Cycle time	Conform to surface
Ergonomics	

Total Number of Criteria: 7
Number of Unique Criteria: 3
Unique Criteria Ratio: 0.43

Problems:

(1) Tool design

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 83

Problem Description: Design of a manufacturing tool for aircraft component production

Criteria Lists:

Electrical Engineer		Mechanical Engineer
Reproducibility		Simple
Robustness	↔	Robust
Functionality		Safety
"Patentability"		

Total Number of Criteria: 7
Number of Unique Criteria: 5
Unique Criteria Ratio: 0.71

Problems:

(1) Tool design

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 86

Problem Description: Design of a manufacturing tool for aircraft component production

Criteria Lists:

Electrical Engineer	Mechanical Engineer
Adequate power	Small machine
Adequate control	Self-indexing
	Self-supporting
	Easy to use
	Little process qualification

Total Number of Criteria: 7
Number of Unique Criteria: 7
Unique Criteria Ratio: 1.00

Problems:

(1) Tool design

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 87

Problem Description: Installation of a new manufacturing tool for aircraft component assembly

Criteria Lists:

Manufacturing Engineer		Manufacturing Engineer
Hold true to fatigue life (1)	◄►	Protection to product (1)
Speed at which force is applied (1)	◄►	Generate all needed features (1)
		Cycle time (2)

Total Number of Criteria: 5
Number of Unique Criteria: 1
Unique Criteria Ratio: 0.20

Problems:

(1) Part quality
(2) Production rate

Total Number of Problems: 2
Number of Unique Problems: 1
Unique Problem Ratio: 0.50

Case ID Number: 88

Problem Description: Problems with test machine during testing of rivet process characteristics

Criteria Lists:

Manufacturing Engineer	Manufacturing Engineer
Integrity of experimental design (1)	Avoid damage to machine (3)
Buy-in from materials technology (2)	
Team comfort (2)	

Total Number of Criteria: 4
Number of Unique Criteria: 4
Unique Criteria Ratio: 1.00

Problems:

(1) Experiment quality
(2) Team dynamics
(3) Damage to testing machine

Total Number of Problems: 3
Number of Unique Problems: 3
Unique Problem Ratio: 1.00

Case ID Number: 98
Problem Description: Manufacturing quality problems during aircraft assembly

Criteria Lists:

Lead DesignEngineer		Manufacturing Engineer
Ensure all aircraft made prior to problem detection are okay (1)	↔	Ensure all prior aircraft are okay (1)
		Adjust planning paperwork (3)
Fix engineering drawings (2)		

Total Number of Criteria: 4
Number of Unique Criteria: 2
Unique Criteria Ratio: 0.50

Problems:

(1) Ensure aircraft made prior to problem detection are okay
(2) Fix engineering drawings
(3) Fix planning paperwork

Total Number of Problems: 3
Number of Unique Problems: 2
Unique Problem Ratio: 0.67

Case ID Number: 100
Problem Description: Redesign and replace a part that was routinely damaged during aircraft assembly

Criteria Lists:

Design Engineer		Design Engineer
Meet stress requirements	↔	Load requirements
Resistant to change		Feasibility
Cost	↔	Budget
Weight		
Repeatability		
Corrossion resistant		

Total Number of Criteria: 9
Number of Unique Criteria: 5
Unique Criteria Ratio: 0.56

Problems:

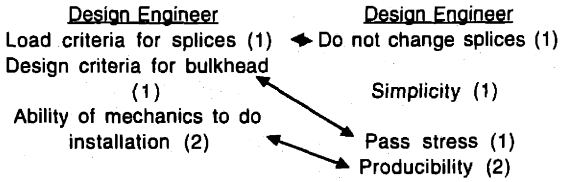
(1) Design fix for problematic part

Total Number of Problems: 1
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 101

Problem Description: Fix operator access/assembly problem during aircraft production

Criteria Lists:



Design Engineer	Design Engineer
Load criteria for splices (1)	Do not change splices (1)
Design criteria for bulkhead (1)	Simplicity (1)
Ability of mechanics to do installation (2)	Pass stress (1)
	Producibility (2)

Total Number of Criteria: 7
Number of Unique Criteria: 1
Unique Criteria Ratio: 0.14

Problems:

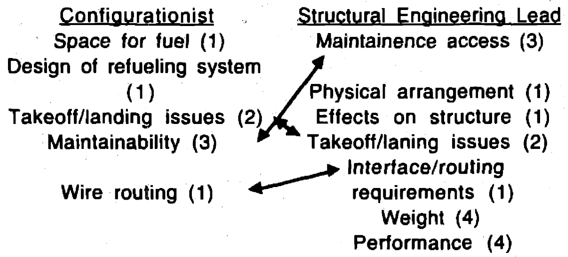
(1) Ensure part meets design requirements
(2) Facilitate operator access

Total Number of Problems: 2
Number of Unique Problems: 0
Unique Problem Ratio: 0.00

Case ID Number: 102

Problem Description: Internal configuration of an aircraft's subsystems

Criteria Lists:



Configurationist	Structural Engineering Lead
Space for fuel (1)	Maintainence access (3)
Design of refueling system (1)	Physical arrangement (1)
Takeoff/landing issues (2)	Effects on structure (1)
Maintainability (3)	Takeoff/laning issues (2)
Wire routing (1)	Interface/routing requirements (1)
	Weight (4)
	Performance (4)

Total Number of Criteria: 12
Number of Unique Criteria: 6
Unique Criteria Ratio: 0.50

Problems:

(1) Internal arrangement
(2) Takeoff/landing issues
(3) Maintainability
(4) Aircraft performance

Total Number of Problems: 4
Number of Unique Problems: 2
Unique Problem Ratio: 0.50

Case ID Number: 103
Problem Description: Repair of a fatigue crack in an aircraft's fuel tank

Criteria Lists:

Tool Design	Design Engineer
Tool design/how to do it? (1)	Reinforce or just clear? (3)
Control of tolerances (1)	Do not damage nearby titanium structure (1)
Accessibility (2)	Avoid removing parts (1)
Cut as drawn? (2)	Could it be done? (1)

Total Number of Criteria: 8
Number of Unique Criteria: 4
Unique Criteria Ratio: 0.50

Problems:

(1) Tool feasibility and repair process
(2) Human accessability
(3) What type of repair to make

Total Number of Problems: 3
Number of Unique Problems: 2
Unique Problem Ratio: 0.67

Case ID Number: 104
Problem Description: Repair of fatigue cracks on an aircraft's bulkhead

Criteria Lists:

Stress Analyst	Design Engineer
Provide a mechanical failsafe (1)	Ensure fix is statically stable (1)
Do not change hole diameter (1)	Accessibility (2)
Maintain stiffness characteristics (1)	Provide needed tools (2)
	Do not damage wing box (1)

Total Number of Criteria: 7
Number of Unique Criteria: 7
Unique Criteria Ratio: 1.00

Problems:

(1) Design of fix for cracked structure
(2) Design of repair process

Total Number of Problems: 2
Number of Unique Problems: 1
Unique Problem Ratio: 0.50

APPENDIX D: MANN-WHITNEY TESTS FOR SIGNIFICANT DIFFERENCES IN OUTCOME MEASURES

Use of Tests vs. Shared Objectives

Ranks

	TEST_OBJ	N	Mean Rank	Sum of Ranks
SAT	1.000	46.000	27.587	1269.000
	2.000	9.000	30.111	271.000
	Total	55.000		
PERF	1.000	47.000	29.585	1390.500
	2.000	9.000	22.833	205.500
	Total	56.000		
COST	1.000	47.000	27.979	1315.000
	2.000	9.000	31.222	281.000
	Total	56.000		
SCH	1.000	47.000	27.117	1274.500
	2.000	9.000	35.722	321.500
	Total	56.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	188.000	160.500	187.000	146.500
Wilcoxon W	1269.000	205.500	1315.000	1274.500
Z	-0.456	-1.170	-0.567	-1.501
Asymp. Sig. (2-tailed)	0.649	0.242	0.571	0.133

a Grouping Variable: TEST_OBJ

Use of Tests vs. Show and Tell

Ranks

	TEST_ST	N	Mean Rank	Sum of Ranks
SAT	1.000	35.000	32.329	1131.500
	2.000	26.000	29.212	759.500
	Total	61.000		
PERF	1.000	36.000	36.583	1317.000
	2.000	26.000	24.462	636.000
	Total	62.000		
COST	1.000	36.000	34.681	1248.500
	2.000	24.000	24.229	581.500
	Total	60.000		
SCH	1.000	36.000	33.583	1209.000
	2.000	25.000	27.280	682.000
	Total	61.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	408.500	285.000	281.500	357.000
Wilcoxon W	759.500	636.000	581.500	682.000
Z	-0.711	-2.712	-2.322	-1.393
Asymp. Sig. (2-tailed)	0.477	0.007	0.020	0.164

a Grouping Variable: TEST_ST

Use of Tests vs. Frequent Face-to-Face Meetings

Ranks

	TEST_MTG	N	Mean Rank	Sum of Ranks
SAT	1.000	47.000	31.766	1493.000
	2.000	15.000	30.667	460.000
	Total	62.000		
PERF	1.000	48.000	34.417	1652.000
	2.000	15.000	24.267	364.000
	Total	63.000		
COST	1.000	48.000	35.240	1691.500
	2.000	15.000	21.633	324.500
	Total	63.000		
SCH	1.000	48.000	33.802	1622.500
	2.000	15.000	26.233	393.500
	Total	63.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	340.000	244.000	204.500	273.500
Wilcoxon W	460.000	364.000	324.500	393.500
Z	-0.217	-1.938	-2.581	-1.426
Asymp. Sig. (2-tailed)	0.828	0.053	0.010	0.154

a Grouping Variable: TEST_MTG

Use of Tests vs. Management Intervention

Ranks

	TEST_MGM	N	Mean Rank	Sum of Ranks
SAT	1.000	51.000	36.196	1846.000
	2.000	15.000	24.333	365.000
	Total	66.000		
PERF	1.000	51.000	36.902	1882.000
	2.000	15.000	21.933	329.000
	Total	66.000		
COST	1.000	51.000	36.059	1839.000
	2.000	14.000	21.857	306.000
	Total	65.000		
SCH	1.000	51.000	37.137	1894.000
	2.000	15.000	21.133	317.000
	Total	66.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	245.000	209.000	201.000	197.000
Wilcoxon W	365.000	329.000	306.000	317.000
Z	-2.185	-2.739	-2.562	-2.914
Asymp. Sig. (2-tailed)	0.029	0.006	0.010	0.004

a Grouping Variable: TEST_MGM

***Shared Objectives vs.
Show and Tell***

Ranks				
	OBJ_ST	N	Mean Rank	Sum of Ranks
SAT	1.000	10.000	28.300	283.000
	2.000	38.000	23.500	893.000
	Total	48.000		
PERF	1.000	10.000	29.750	297.500
	2.000	38.000	23.118	878.500
	Total	48.000		
COST	1.000	10.000	30.200	302.000
	2.000	36.000	21.639	779.000
	Total	46.000		
SCH	1.000	10.000	32.200	322.000
	2.000	37.000	21.784	806.000

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	152.000	137.500	113.000	103.000
Wilcoxon W	893.000	878.500	779.000	806.000
Z	-1.017	-1.380	-1.828	-2.182
Asymp. Sig. (2-tailed)	0.309	0.168	0.068	0.029
Exact Sig. [2*(1-tailed Sig.)]	0.347	0.186	0.076	0.033

a Not corrected for ties.
b Grouping Variable: OBJ_ST

***Shared Objectives vs.
Frequent Face-to-Face
Meetings***

Ranks

	OBJ_MTGS	N	Mean Rank	Sum of Ranks
SAT	1.000	14.000	19.393	271.500
	2.000	19.000	15.237	289.500
	Total	33.000		
PERF	1.000	14.000	19.071	267.000
	2.000	19.000	15.474	294.000
	Total	33.000		
COST	1.000	14.000	22.321	312.500
	2.000	19.000	13.079	248.500
	Total	33.000		
SCH	1.000	14.000	23.107	323.500
	2.000	19.000	12.500	237.500
	Total	33.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	99.500	104.000	58.500	47.500
Wilcoxon W	289.500	294.000	248.500	237.500
Z	-1.328	-1.136	-2.788	-3.197
Asymp. Sig. (2-tailed)	0.184	0.256	0.005	0.001
Exact Sig. [2*(1-tailed Sig.)]	0.226	0.304	0.005	0.001

a Not corrected for ties.
b Grouping Variable: OBJ_MTGS

***Shared Objectives vs.
Management
Intervention***

Ranks

	OBJ_MGMT	N	Mean Rank	Sum of Ranks
SAT	1.000	15.000	20.233	303.500
	2.000	16.000	12.031	192.500
	Total	31.000		
PERF	1.000	15.000	19.533	293.000
	2.000	17.000	13.824	235.000
	Total	32.000		
COST	1.000	15.000	20.400	306.000
	2.000	16.000	11.875	190.000
	Total	31.000		
SCH	1.000	15.000	23.000	345.000
	2.000	17.000	10.765	183.000
	Total	32.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	56.500	82.000	54.000	30.000
Wilcoxon W	192.500	235.000	190.000	183.000
Z	-2.590	-1.783	-2.681	-3.767
Asymp. Sig. (2-tailed)	0.010	0.075	0.007	0.000
Exact Sig. [2*(1-tailed Sig.)]	0.011	0.089	0.008	0.000

a Not corrected for ties.

b Grouping Variable: OBJ_MGMT

***Show and Tell vs.
Frequent Face-to-Face
Meetings***

Ranks

	ST_MTGS	N	Mean Rank	Sum of Ranks
SAT	1.000	32.000	20.703	662.500
	2.000	9.000	22.056	198.500
	Total	41.000		
PERF	1.000	32.000	20.672	661.500
	2.000	9.000	22.167	199.500
	Total	41.000		
COST	1.000	30.000	21.100	633.000
	2.000	9.000	16.333	147.000
	Total	39.000		
SCH	1.000	31.000	21.597	669.500
	2.000	9.000	16.722	150.500
	Total	40.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	134.500	133.500	102.000	105.500
Wilcoxon W	662.500	661.500	147.000	150.500
Z	-0.314	-0.343	-1.132	-1.124
Asymp. Sig. (2-tailed)	0.754	0.732	0.258	0.261
Exact Sig. [2*(1-tailed Sig.)]	0.769	0.745	0.264	0.276

a Not corrected for ties
b Grouping Variable: ST_MTGS

Show and Tell vs. Management Intervention

Ranks

	ST_MGMT	N	Mean Rank	Sum of Ranks
SAT	1.000	34.000	22.441	763.000
	2.000	7.000	14.000	98.000
	Total	41.000		
PERF	1.000	34.000	22.926	779.500
	2.000	8.000	15.438	123.500
	Total	42.000		
COST	1.000	33.000	21.939	724.000
	2.000	8.000	17.125	137.000
	Total	41.000		
SCH	1.000	33.000	22.985	758.500
	2.000	8.000	12.813	102.500
	Total	41.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	70.000	87.500	101.000	66.500
Wilcoxon W	98.000	123.500	137.000	102.500
Z	-1.765	-1.589	-1.056	-2.214
Asymp. Sig. (2-tailed)	0.077	0.112	0.290	0.027
Exact Sig. [2*(1-tailed Sig.)]	0.093	0.122	0.322	0.029

a Not corrected for ties.
b Grouping Variable: ST_MGMT

Frequent Face-to-Face Meetings vs. Management Intervention

Ranks

	MTGS_MGM	N	Mean Rank	Sum of Ranks
SAT	1.000	17.000	18.912	321.500
	2.000	13.000	11.038	143.500
	Total	30.000		
PERF	1.000	17.000	17.235	293.000
	2.000	14.000	14.500	203.000
	Total	31.000		
COST	1.000	17.000	15.853	269.500
	2.000	13.000	15.038	195.500
	Total	30.000		
SCH	1.000	17.000	18.324	311.500
	2.000	14.000	13.179	184.500
	Total	31.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	52.500	98.000	104.500	79.500
Wilcoxon W	143.500	203.000	195.500	184.500
Z	-2.536	-0.859	-0.279	-1.626
Asymp. Sig. (2-tailed)	0.011	0.390	0.781	0.104
Exact Sig. [2*(1-tailed Sig.)]	0.014	0.421	0.805	0.118

a Not corrected for ties.
b Grouping Variable: MTGS_MGM

Co-location vs. Use of Tests

Ranks

	COL_TEST	N	Mean Rank	Sum of Ranks
SAT	1.000	4.000	24.125	96.500
	2.000	45.000	25.078	1128.500
	Total	49.000		
PERF	1.000	4.000	32.500	130.000
	2.000	46.000	24.891	1145.000
	Total	50.000		
COST	1.000	3.000	14.500	43.500
	2.000	46.000	25.685	1181.500
	Total	49.000		
SCH	1.000	3.000	23.667	71.000
	2.000	46.000	25.087	1154.000
	Total	49.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	86.500	64.000	37.500	65.000
Wilcoxon W	96.500	1145.000	43.500	71.000
Z	-0.134	-1.037	-1.352	-0.171
Asymp. Sig. (2-tailed)	0.894	0.300	0.176	0.864
Exact Sig. [2*(1-tailed Sig.)]	0.902	0.339	0.200	0.891

a Not corrected for ties.
b Grouping Variable: COL_TEST

Co-location vs. Shared Objectives

Ranks

	COL_OBJ	N	Mean Rank	Sum of Ranks
SAT	1.000	14.000	16.643	233.000
	2.000	18.000	16.389	295.000
	Total	32.000		
PERF	1.000	14.000	21.464	300.500
	2.000	18.000	12.639	227.500
	Total	32.000		
COST	1.000	13.000	15.577	202.500
	2.000	18.000	16.306	293.500
	Total	31.000		
SCH	1.000	13.000	14.500	188.500
	2.000	18.000	17.083	307.500
	Total	31.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	124.000	56.500	111.500	97.500
Wilcoxon W	295.000	227.500	202.500	188.500
Z	-0.081	-2.979	-0.226	-0.801
Asymp. Sig. (2-tailed)	0.935	0.003	0.821	0.423
Exact Sig. [2*(1-tailed Sig.)]	0.955	0.007	0.826	0.441

a Not corrected for ties.
b Grouping Variable: COL_OBJ

Co-location vs. Show and Tell

Ranks

	COL_ST	N	Mean Rank	Sum of Ranks
SAT	1.000	7.000	24.786	173.500
	2.000	39.000	23.269	907.500
	Total	46.000		
PERF	1.000	7.000	37.786	264.500
	2.000	39.000	20.936	816.500
	Total	46.000		
COST	1.000	7.000	23.643	165.500
	2.000	38.000	22.882	869.500
	Total	45.000		
SCH	1.000	7.000	27.429	192.000
	2.000	39.000	22.795	889.000
	Total	46.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	127.500	36.500	128.500	109.000
Wilcoxon W	907.500	816.500	869.500	889.000
Z	-0.288	-3.138	-0.148	-0.865
Asymp. Sig. (2-tailed)	0.773	0.002	0.883	0.387
Exact Sig. [2*(1-tailed Sig.)]	0.788	0.001	0.890	0.417

a Not corrected for ties.

b Grouping Variable: COL_ST

Co-location vs. Frequent Face-to-Face Meetings

Ranks

	COL_MTGS	N	Mean Rank	Sum of Ranks
SAT	1.000	15.000	22.500	337.500
	2.000	24.000	18.438	442.500
	Total	39.000		
PERF	1.000	15.000	27.267	409.000
	2.000	24.000	15.458	371.000
	Total	39.000		
COST	1.000	14.000	23.714	332.000
	2.000	24.000	17.042	409.000
	Total	38.000		
SCH	1.000	14.000	23.250	325.500
	2.000	24.000	17.313	415.500
	Total	38.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	142.500	71.000	109.000	115.500
Wilcoxon W	442.500	371.000	409.000	415.500
Z	-1.167	-3.310	-1.830	-1.638
Asymp. Sig. (2-tailed)	0.243	0.001	0.067	0.101
Exact Sig. [2*(1-tailed Sig.)]	0.283	0.001	0.076	0.113

a Not corrected for ties.

b Grouping Variable: COL_MTGS

Co-location vs. Management Intervention

Ranks

	COL_MGMT	N	Mean Rank	Sum of Ranks
SAT	1.000	15.000	22.500	337.500
	2.000	20.000	14.625	292.500
	Total	35.000		
PERF	1.000	15.000	25.833	387.500
	2.000	21.000	13.262	278.500
	Total	36.000		
COST	1.000	14.000	20.357	285.000
	2.000	20.000	15.500	310.000
	Total	34.000		
SCH	1.000	14.000	22.750	318.500
	2.000	21.000	14.833	311.500
	Total	35.000		

Test Statistics

	SAT	PERF	COST	SCH
Mann-Whitney U	82.500	47.500	100.000	80.500
Wilcoxon W	292.500	278.500	310.000	311.500
Z	-2.359	-3.688	-1.442	-2.287
Asymp. Sig. (2-tailed)	0.018	0.000	0.149	0.022
Exact Sig. [2*(1-tailed Sig.)]	0.023	0.000	0.169	0.024

a Not corrected for ties.

b Grouping Variable: COL_MGMT

APPENDIX E: CHI-SQUARED COMPARISONS OF FACTOR CITATION FREQUENCIES BETWEEN EASY AND DIFFICULT CASES

Following are chi-squared analyses comparing the frequency with which factors were cited in easy and difficult cases. Instances of significant difference are highlighted and labeled "Significant".

Easy vs. Difficult Factor Frequency Comparisons

Note: 1 degree of freedom: significance at 0.05 level requires 3.84

Total N's	
Easy	33
Difficult	65

Factor: **Management Intervention**

Number of Times Cited	
Easy	2
Difficult	19

χ^2=6.98	Significant

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	31	2	*33*
	Difficult	46	19	*65*
	Residuals	*77*	*21*	*98 =N*

Frequencies		
	25.92857	7.071429
	51.07143	13.92857

Factor: **Critical Team Member**

Number of Times Cited	
Easy	6
Difficult	7

χ^2=1.05

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	27	6	*33*
	Difficult	58	7	*65*
	Residuals	*85*	*13*	*98 =N*

Frequencies		
	28.62	4.38
	56.38	8.62

Factor: **Engineering Expertise**

Number of Times Cited	
Easy	5
Difficult	6

χ^2=0.77

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	28	5	*33*	
	Difficult	59	6	*65*	
	Residuals	*87*	*11*		*98 =N*

Frequencies	29.30	3.70
	57.70	7.30

Factor: **Trade Studies**

Number of Times Cited	
Easy	0
Difficult	8

χ^2=4.42 Significant

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	33	0	*33*	
	Difficult	57	8	*65*	
	Residuals	*90*	*8*		*98 =N*

Frequencies	30.31	2.69
	59.69	5.31

Factor: **Show and Tell**

Number of Times Cited	
Easy	14
Difficult	34

χ^2=0.86

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	19	14	*33*	
	Difficult	31	34	*65*	
	Residuals	*50*	*48*		*98 =N*

Frequencies	16.84	16.16
	33.16	31.84

Factor: **Used Tests**

Number of Times Cited	
Easy	19
Difficult	38

χ^2=0.01

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	14	19	*33*	
	Difficult	27	38	*65*	
	Residuals	*41*	*57*		*98 =N*

Frequencies	13.81	19.19
	27.19	37.81

Factor: Time Pressure

Number of Times Cited	
Easy	4
Difficult	8

χ^2=0.00

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	29	4	*33*
	Difficult	57	8	*65*
	Residuals	*86*	*12*	*98 =N*

Frequencies	28.96	4.04
	57.04	7.96

Factor: Co-Located

Number of Times Cited	
Easy	7
Difficult	8

χ^2=1.34

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	26	7	*33*
	Difficult	57	8	*65*
	Residuals	*83*	*15*	*98 =N*

Frequencies	27.95	5.05
	55.05	9.95

Factor: Frequent Face-to-Face Meetings

Number of Times Cited	
Easy	8
Difficult	16

χ^2=0.00

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	25	8	*33*
	Difficult	49	16	*65*
	Residuals	*74*	*24*	*98 =N*

Frequencies	24.92	8.08
	49.08	15.92

Factor: Shared Objectives

Number of Times Cited	
Easy	10
Difficult	9

χ^2=3.79

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	23	10	*33*
	Difficult	56	9	*65*
	Residuals	*79*	*19*	*98 =N*

Frequencies	26.60	6.40
	52.40	12.60

Factor: **Win-Win Solution Created**

Number of Times Cited	
Easy	3
Difficult	0

χ^2=6.10 Significant

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	30	3	*33*	
	Difficult	65	0	*65*	
	Residuals	*95*	*3*		*98 =N*

Frequencies	31.99	1.01
	63.01	1.99

Factor: **Explained Reasons Why**

Number of Times Cited	
Easy	4
Difficult	3

χ^2=1.86

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	29	4	*33*	
	Difficult	62	3	*65*	
	Residuals	*91*	*7*		*98 =N*

Frequencies	30.64	2.36
	60.36	4.64

Factor: **Social Problems**

Number of Times Cited	
Easy	5
Difficult	27

χ^2=6.93 Significant

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	28	5	*33*	
	Difficult	38	27	*65*	
	Residuals	*66*	*32*		*98 =N*

Frequencies	22.22	10.78
	43.78	21.22

Factor: **Misused Boundary Objects**

Number of Times Cited	
Easy	1
Difficult	6

χ^2=1.27

		Factor			
		Absent	Present	*Residuals*	
Difficulty	Easy	32	1	*33*	
	Difficult	59	6	*65*	
	Residuals	*91*	*7*		*98 =N*

Frequencies	30.64	2.36
	60.36	4.64

Factor: **Lack of Shared Metrics/Objectives**

χ^2=6.29	Significant

Number of Times Cited	
Easy	0
Difficult	11

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	33	0	*33*
	Difficult	54	11	*65*
	Residuals	*87*	*11*	*98 =N*

Frequencies		
	29.30	3.70
	57.70	7.30

Factor: **Unclear Lines of Comm/Auth**

χ^2=2.24

Number of Times Cited	
Easy	2
Difficult	11

		Factor		
		Absent	Present	*Residuals*
Difficulty	Easy	31	2	*33*
	Difficult	54	11	*65*
	Residuals	*85*	*13*	*98 =N*

Frequencies		
	28.62	4.38
	56.38	8.62

APPENDIX F: REGRESSIONS ANALYSES

(Begin on the next page)

Regression, Stepwise, for Performance

Variables Entered/Removed

Model	Variables Entered	Variables Removed	Method
1.000	COLOC	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a Dependent Variable: PERF

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1.000	0.357	0.127	0.115	1.160

a Predictors: (Constant), COLOC

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1.000	Regression	13.540	1.000	13.540	10.065	0.002
	Residual	92.826	69.000	1.345		
	Total	106.366	70.000			

a Predictors: (Constant), COLOC

b Dependent Variable: PERF

Coefficients

		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model		B	Std. Error	Beta		
1.000	(Constant)	5.085	0.151		33.673	0.000
	COLOC	1.165	0.367	0.357	3.172	0.002

a Dependent Variable: PERF

Excluded Variables

		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
Model						Tolerance
1.000	MGMT	0.002	0.019	0.985	0.002	0.963
	CRIT_MEM	0.098	0.853	0.396	0.103	0.972
	ENG_EXP	-0.175	-1.549	0.126	-0.185	0.974
	TRADE	-0.106	-0.931	0.355	-0.112	0.981
	BO	-0.109	-0.968	0.337	-0.117	0.998
	TEST	0.147	1.310	0.195	0.157	0.991
	TIME	0.093	0.829	0.410	0.100	0.999
	MTGS	0.048	0.413	0.681	0.050	0.941
	OBJ	0.078	0.684	0.496	0.083	0.983
	WIN_WIN	-0.015	-0.129	0.898	-0.016	0.991
	REAS_WHY	-0.116	-1.036	0.304	-0.125	0.999
	SOCPROB	0.149	1.329	0.188	0.159	0.999
	BAD_BO	-0.021	-0.188	0.852	-0.023	0.981
	BAD_MET	-0.111	-0.976	0.332	-0.118	0.985
	BAD_COM	0.066	0.583	0.562	0.071	0.994

a Predictors in the Model: (Constant), COLOC

b Dependent Variable: PERF

Regression, Stepwise, For Cost

Variables Entered/Removed

Model	Variables Entered	Variables Removed	Method
1.000	TEST	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2.000	OBJ	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a Dependent Variable: COST

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1.000	0.338	0.115	0.101	1.393
2.000	0.485	0.235	0.212	1.305

a Predictors: (Constant), TEST

b Predictors: (Constant), TEST, OBJ

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1.000	Regression	16.812	1.000	16.812	8.664	0.004
	Residual	130.000	67.000	1.940		
	Total	146.812	68.000			
2.000	Regression	34.493	2.000	17.246	10.134	0.000
	Residual	112.319	66.000	1.702		
	Total	146.812	68.000			

a Predictors: (Constant), TEST

b Predictors: (Constant), TEST, OBJ

c Dependent Variable: COST

Coefficients

		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model		B	Std. Error	Beta		
1.000	(Constant)	4.000	0.259		15.464	0.000
	TEST	1.000	0.340	0.338	2.944	0.004
2.000	(Constant)	3.695	0.260		14.209	0.000
	TEST	1.084	0.319	0.367	3.395	0.001
	OBJ	1.263	0.392	0.348	3.223	0.002

a Dependent Variable: COST

Excluded Variables

		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
Model						Tolerance
1.000	MGMT	0.090	0.755	0.453	0.093	0.946
	CRIT_MEM	-0.095	-0.817	0.417	-0.100	0.977
	ENG_EXP	-0.031	-0.268	0.789	-0.033	0.999
	TRADE	0.156	1.352	0.181	0.164	0.984
	BO	-0.043	-0.359	0.721	-0.044	0.932
	TIME	-0.118	-1.027	0.308	-0.125	1.000
	MTGS	-0.193	-1.682	0.097	-0.203	0.975
	OBJ	0.348	3.223	0.002	0.369	0.993
	WIN_WIN	-0.049	-0.424	0.673	-0.052	0.989
	REAS_WHY	-0.161	-1.374	0.174	-0.167	0.954
	SOCPROB	0.069	0.583	0.562	0.072	0.951
	BAD_BO	0.141	1.233	0.222	0.150	0.998
	BAD_MET	-0.080	-0.680	0.499	-0.083	0.954
	BAD_COM	0.000	0.000	1.000	0.000	1.000
	COLOC	0.000	0.000	1.000	0.000	0.983
2.000	MGMT	0.060	0.540	0.591	0.067	0.939
	CRIT_MEM	-0.066	-0.604	0.548	-0.075	0.971
	ENG_EXP	-0.008	-0.070	0.945	-0.009	0.994
	TRADE	0.106	0.966	0.338	0.119	0.963
	BO	-0.033	-0.292	0.772	-0.036	0.932
	TIME	-0.051	-0.466	0.643	-0.058	0.961
	MTGS	-0.153	-1.401	0.166	-0.171	0.961
	WIN_WIN	-0.071	-0.650	0.518	-0.080	0.985
	REAS_WHY	-0.106	-0.945	0.348	-0.116	0.928
	SOCPROB	0.064	0.578	0.565	0.072	0.951
	BAD_BO	0.202	1.889	0.063	0.228	0.972
	BAD_MET	-0.073	-0.662	0.511	-0.082	0.953
	BAD_COM	-0.006	-0.055	0.956	-0.007	0.999
	COLOC	0.040	0.361	0.719	0.045	0.971

a **Predictors in the Model:** (Constant), TEST

b **Predictors in the Model:** (Constant), TEST, OBJ

c **Dependent Variable:** COST

Regression, Stepwise, for Schedule

Variables Entered/Removed

Model	Variables Entered	Variables Removed	Method
1.000	TEST	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2.000	OBJ	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a Dependent Variable: SCH

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1.000	0.309	0.095	0.082	1.534
2.000	0.448	0.200	0.177	1.452

a Predictors: (Constant), TEST

b Predictors: (Constant), TEST, OBJ

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1.000	Regression	16.858	1.000	16.858	7.167	0.009
	Residual	159.942	68.000	2.352		
	Total	176.800	69.000			
2.000	Regression	35.448	2.000	17.724	8.401	0.001
	Residual	141.352	67.000	2.110		
	Total	176.800	69.000			

a Predictors: (Constant), TEST

b Predictors: (Constant), TEST, OBJ

c Dependent Variable: SCH

Coefficients

		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model		B	Std. Error	Beta		
1.000	(Constant)	3.833	0.280		13.690	0.000
	TEST	0.992	0.370	0.309	2.677	0.009
2.000	(Constant)	3.532	0.284		12.438	0.000
	TEST	1.067	0.352	0.332	3.034	0.003
	OBJ	1.292	0.435	0.325	2.968	0.004

a Dependent Variable: SCH

Excluded Variables

		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
Model						Tolerance
1.000	MGMT	-0.136	-1.143	0.257	-0.138	0.932
	CRIT_MEM	-0.019	-0.158	0.875	-0.019	0.980
	ENG_EXP	-0.074	-0.641	0.524	-0.078	0.998
	TRADE	0.033	0.286	0.776	0.035	0.997
	BO	0.025	0.207	0.837	0.025	0.925
	TIME	-0.085	-0.732	0.467	-0.089	0.997
	MTGS	-0.181	-1.569	0.121	-0.188	0.978
	WIN_WIN	-0.067	-0.574	0.568	-0.070	0.990
	REAS_WHY	0.031	0.259	0.797	0.032	0.957
	SOCPROB	-0.074	-0.625	0.534	-0.076	0.948
	BAD_BO	-0.031	-0.270	0.788	-0.033	0.998
	BAD_MET	-0.006	-0.049	0.961	-0.006	0.957
	BAD_COM	-0.111	-0.957	0.342	-0.116	0.997
	COLOC	0.174	1.505	0.137	0.181	0.982
	OBJ	0.325	2.968	0.004	0.341	0.995
2.000	MGMT	-0.158	-1.401	0.166	-0.170	0.928
	CRIT_MEM	0.007	0.065	0.948	0.008	0.974
	ENG_EXP	-0.053	-0.485	0.629	-0.060	0.994
	TRADE	-0.001	-0.013	0.990	-0.002	0.985
	BO	0.037	0.323	0.747	0.040	0.924
	TIME	-0.018	-0.157	0.876	-0.019	0.953
	MTGS	-0.146	-1.316	0.193	-0.160	0.966
	WIN_WIN	-0.088	-0.798	0.428	-0.098	0.986
	REAS_WHY	0.085	0.750	0.456	0.092	0.933
	SOCPROB	-0.080	-0.710	0.480	-0.087	0.948
	BAD_BO	0.020	0.180	0.858	0.022	0.973
	BAD_MET	-0.001	-0.006	0.995	-0.001	0.956
	BAD_COM	-0.109	-0.998	0.322	-0.122	0.997
	COLOC	0.212	1.950	0.055	0.233	0.970

a Predictors in the Model: (Constant), TEST

b Predictors in the Model: (Constant), TEST, OBJ

c Dependent Variable: SCH

APPENDIX G: METHODS TUTORIAL

Introduction

The following sections are intended as a tutorial for future researchers who might wish to make use of the methods pioneered in this study. This tutorial first discusses when these methods should be used and then describes how to calculate the measures upon which its relies. Examples of potential hypotheses are presented, along with potential performance measures, interview questions, and other suggestions about conducting a successful case interview. The tutorial concludes with a discussion of how the methods could be adapted for near-real-time data collection.

Why and When This Method Should Be Used

The following data collection approach was developed in order to study communication practices on product development teams. Specifically, these methods are intended to provide insight into how engineers interpret design problems, how those interpretations can vary, what factors can change those interpretations, and what impact differences in interpretation can have on problem solving performance. The approach was initially applied using case interviews; as of this writing, no attempt had been made to use it as part of a written survey. It is the recommendation of the author that any researcher planning to use this approach in a survey first conduct interviews to gain experience with the methods, and only then attempt to modify for them use in written surveys.

The benefit of the approach developed for this study was that it provided a means of quantifying the differences between two (or more) engineers' interpretations of a design problem. While previous studies have noted that engineers from different groups tended to focus on different aspects of a design problem, few researchers have been able to quantify such differences. By comparing criteria lists, as described below, the approach used in this study facilitated such numerical comparisons, opening up a broad range of potential statistical analyses and performance assessments.

The following instructions reflect lessons learned during the original study and include several modifications and improvements.

The Unique Criteria Ratio and the Awareness Ratio: The Basics

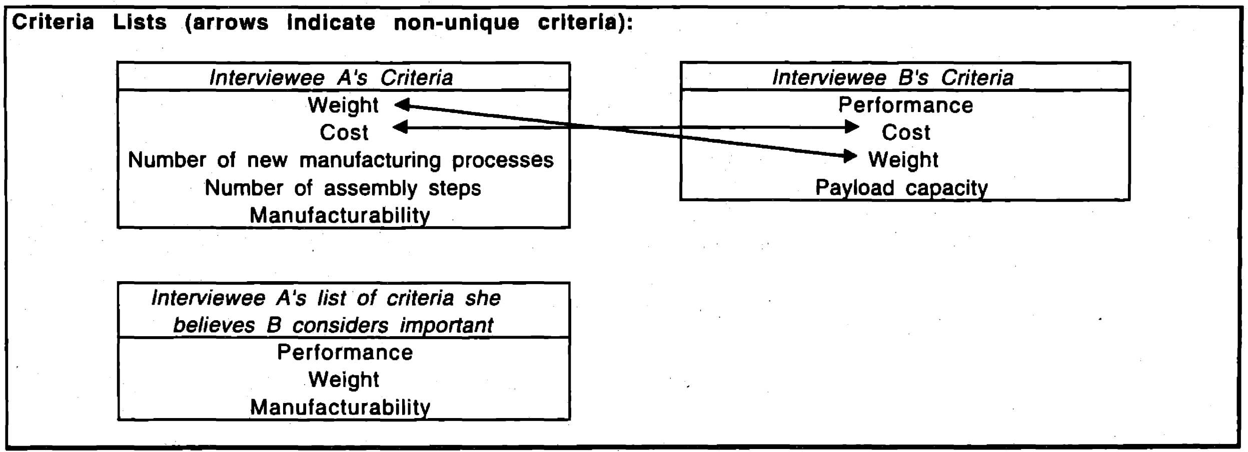
The method to quantify problem interpretations centers on collecting criteria lists from study participants. For each problem solving case that is described, the interviewee is asked to provide two lists of criteria (see "The Basic Historical Interview" below). First, the interviewee should list the criteria or factors that he or she used to judge the benefits or drawbacks of potential solutions. Then, the interviewee should be prompted to provide a list of the criteria he or she believes were important to the other members of the team. Examples of criteria include recurring cost, ease of use, number of parts, range, weight, etc.

For a given case, at least two interviews must be conducted. If possible, each interviewee should be from different specialty groups, though the method still works even if the interviewees are from the same specialty group. The difference in problem interpretation between two individuals can then be quantified using the *unique criteria ratio*, which measures how similar two engineers' interpretations of a problem are, and the *awareness ratio*, which measures how well one engineer understands another engineer's concerns. The following paragraphs use illustrative examples to demonstrate how each ratio is calculated and these calculations are depicted in the tables below.

The unique criteria ratio is determined by dividing the number of criteria that were cited by only one person by the total number of criteria cited by both interviewees. Thus, the closer this ratio is to zero, the more similar two individual's interpretations of a problem were. For example, suppose the first interviewee cited *weight*, *cost*, *number of new manufacturing processes*, *number of assembly steps,* and *manufacturability* as her criteria, while the second interviewee cited *performance*, *cost*, *weight*, and *payload capacity*. The total number of criteria cited is nine. Since both cited *cost* and *weight*, those two criteria are not unique. The criteria *number of parts*, *number of assembly steps*, *number of new manufacturing processes*, *manufacturability*, *performance*, and *payload capacity*, on the other hand, were each only cited by one of the two interviewees. Therefore, those criteria are considered "unique" and the ratio would be 0.56 (five unique criteria divided by nine total criteria).

The awareness ratio is calculated in a similar fashion. The numerator for this ratio is the number of criteria that the first interviewee *incorrectly* cited as important to the second interviewee *plus* the number of criteria cited by the second interviewee that first failed to cite. The denominator is the total number of criteria actually cited as important by the second interviewee. Therefore, when the awareness ratio is zero, the first interviewee was able to exactly cite the criteria list of the second interviewee. (Note, then, that both the awareness ratio and the unique criteria ratio improve as they approach zero). So, suppose in the example above, the first interviewee had stated that she believed that the other interviewee's criteria were *performance*, *weight*, and *manufacturability*. The numerator of the *awareness ratio* would be three (she failed to mention *cost* and *payload capacity* and incorrectly cited *manufacturability*), and the denominator would be four (since the second interviewee actually cited four criteria: *performance*, *cost*, *weight*, and *payload capacity*). Thus, the awareness ratio for this example would be 0.75.

These calculations are illustrated in the tables below:



Criteria Lists (arrows indicate non-unique criteria):

Interviewee A's Criteria
Weight
Cost
Number of new manufacturing processes
Number of assembly steps
Manufacturability

Interviewee B's Criteria
Performance
Cost
Weight
Payload capacity

Interviewee A's list of criteria she believes B considers important
Performance
Weight
Manufacturability

Unique Criteria Ratio Calculation

Total number of criteria:	5+4 = 9
Number of unique criteria:	5
Unique Criteria Ratio:	5 / 9

Awareness Ratio Calculation (for A relative to B)

Number of incorrect criteria:	1
Number of ommitted criteria:	2
Numerator:	1+ 2 = 3
Total number of criteria actually cited by B:	4
Awareness Ratio:	3 / 4

In the original study, only two people were interviewed for each case. If more than two individuals are interviewed, the ratios should still be calculated in a paired fashion. The team's performance as a whole can then be judge by calculating an *average* unique criteria ratio and an *average* awareness ratio.

Hypotheses to Test

Using these two measures, two sets of hypotheses can be tested. The first set relates to the effect of problem interpretations on problem solving performance. Thus, one might hypothesize that the closer the unique problem and awareness ratios are to zero, the better the team will be able to solve the problem (see "Measuring Problem Solving Performance" below).

The second set of hypotheses address how problem interpretations can be affected. For example, one could hypothesize that engineers from the same specialty will have smaller unique criteria ratios than engineers from different specialties. In addition, one could investigate the effects of various design tools and methods on problem interpretations. For instance, one might propose that members of design teams that conducted extensive testing will have smaller awareness ratios (that is, tests help engineers understand one another's needs). Any study of design team problem solving should endeavor to address both types of questions.

Measuring Problem Solving Performance

The original study used subjective measures of performance. A major improvement to these methods, however, would be to replace these subjective measures with more "concrete" values. Potential data that could be used to measure problem solving performance include:

- Number of engineering changes made to the product element under study.
- Number of parts or components that were changed.
- Number of subsystems that were affected by the solution.
- Time required to solve the problem.
- Impact of solution on product performance (for example, increased weight, reduced range, etc.).
- Impact of solution on product cost (non-recurring and/or recurring).

In general, researchers should attempt to gather data on as many performance measures as possible – individual measures can be unreliable, so having multiple options will improve the likelihood of finding meaningful relationships. A variety of studies exist on what measures best indicate product development performance, and future researchers are encouraged to supplement the above list with metrics used in other studies.

The Basic Historical Interview

The fundamental aspect of the method is the case interview. A study participant is asked to describe a recent problem that he or she solved while working as part of a product development team. The interview has four distinct, but related, goals: (1) to understand the context and basic details of the case under investigation; (2) to ascertain how the problem was solved and identify the most important factors facilitating or inhibiting the problem solving process; (3) to collect data on how the participant interpreted the problem; and (4) to collect performance data.

It is important that the interviewer initially ask a series of questions that allow the participant to discuss the case at his or her own pace. Such questions facilitate recall and help the participant to "get back into" the experience. Then, as the details of the case emerge, more targeted questions can be asked. Finally, it is worthwhile to ask the same question in several different ways. Such repetition ensures that the interviewer has captured the details that the participant considers important and also aids the participant's recall of the case's details.

Example Interview Questions

Following is an example of the set of questions that might be asked during an interview. Note that questions are included to collect criteria lists as well as to elicit other specifics about the problem solving effort. Additional suggestions and guidelines are given in *italics* under some questions.

(1) Please briefly describe the initial situation – what was the problem?
(Note: The interviewer should allow the interviewee to provide an overall perspective of the case when he or she responds to this question. Such details will allow the interviewer to tailor later questions based on the information provided by the interviewee.)

(2) What *design* criteria did you use to evaluate potential solutions to the problem?
(Note: If the interviewee is confused by this question, the interviewer might first consider rephrasing it [for example, "How did you judge whether or not a design was good or bad?"], and then, if the interviewee is still having trouble, by providing examples [such as cost or weight]. However, providing examples introduces the risk of biasing the interviewee [he might respond by citing the examples just given to him], so the interviewer should avoid this option.)

(3) What *design* criteria do you believe [the other team member] used to evaluate potential solutions to the problem?
(Note: This question must be asked once for each of the other team members participating in the study – if there are five people on the team [other than the current interviewee], the question must be asked five times, once for each person.)

(4) How was the problem finally resolved, or what was the solution to the problem?

(5) What specific events do you believe were most important to reaching a solution?

(6) Were any tools (drawings, CAD models, prototypes, etc.) useful in reaching a consensus?

(7) Was any one person most responsible for the solution or in changing your opinion of the situation?

(8) How many design alternatives did you consider in attempting to resolve the problem, and how were those alternatives considered: in series, in parallel, etc.?

(9) What events or factors were *most critical* to resolving the issue?

As noted above, several of the questions are somewhat repetitious. During the initial study, such repetition was found to be beneficial: asking the same question in a different way often elicited additional details about a case and helped to clarify earlier points. If the interviewer feels as though a question may appear extremely repetitious, he or she may say to the interviewee, "You have already touched on some of these issues, but let me ask..." and then go on to ask the next question. This researcher made extensive use of such techniques, and found that interviewees responded positively to them.

Once the descriptive questions have been completed, the interviewer should then collect performance data. The nature of the performance data that is acquired (subjective or "concrete") will clearly affect the details of this next phase of the interview. No attempt will be made, therefore, to provide specific instructions for such efforts.

Other Notes about the Interview

Prior to starting the interview, several points should be made clear to each interviewee. First, assure him or her that his or her personal performance is *not* being evaluated. Second, be sure to inform the interviewee that all of his or her responses will be kept confidential. Finally, review with the interviewee any proprietary information protection agreements that may be in place with his or her company. An example of such introductory information follows:

> The goal of this interview is to learn about how you have solved problems in a multidisciplinary environment. There are no right or wrong answers, nor am I evaluating your personal performance.
>
> Please be aware that I will consider our entire discussion confidential. No details of our talk will be released publicly without prior approval from your company. Furthermore, your name, your company's name, and your project's name will never appear in any of the written or electronic papers or presentations that result from this study.

Adapting the Methods for Near-Real-Time Use

The original version of this study collected data using historical case interviews. A significant improvement to the approach, however, would be to collect data in near-real-time. Such a study would consist of three main phases. First, initial interviews are conducted with each participant. During these interviews, participants are briefed about the goals of the study as well as what will be asked of them. Each participant is asked to provide a description of the problem to be followed from his or her point of view. The interviewee is also prompted to provide a list of his or her own criteria as well as the criteria he or she believes to be important to each of the other members of the team.

The second phase of study occurs *as the team is trying to solve the problem.* On random days, the participants are asked to again state their criteria lists and their guesses as to the other members' lists. The researcher should evaluate the potential drawbacks or benefits of providing the participants with their previous responses – providing such information could simplify the response process for the participants but it could also bias their responses. Several possible methods could be used to solicit these updated lists, including a web page, email, a telephone call, an interview, or a mailed letter. In general, the researcher should strive to interfere as little as possible in the participants' day-to-day activities.

The frequency of sampling should be scaled with the problem under study. For complex problems that are solved over several months, data may only need to be collected once a week. Problems with shorter cycle times may require more frequent data collection, such as twice a week or once a day.

Unique criteria and awareness ratios are calculated for each sample. When significant changes are noted, the researcher should then conduct a quick interview (by phone or, if possible, in person) to ascertain what might have caused the change. During such an interview, the researcher should *not* say, "I noticed a significant change in your criteria list, Maya..." Instead, the researcher should begin the interview simply by asking the participant to explain what has happened recently. Such an open-ended question will likely be answered with a description of recent major events, some of which are likely to explain the change in criteria lists. Additional standardized questions could then be asked (refer to the example interview questions given above).

Finally, once the problem has been solved, performance data is collected (see above). This performance data can then be linked to any trends that were noted in the unique criteria ratio, awareness ratio, or to any major events that occurred during the problem solving effort. Such a study would likely provide even greater insights into problem solving processes and problem interpretation than have historical investigations.