

# 1. Introduction and Scope of Research

## 1.1. Introduction

The increasing globalization of industry is causing an acceleration in the pace of product change (Salomone, 1995). The ability to introduce new products faster, more frequently, and of higher quality is a distinct competitive advantage (Liker, Sobek, Ward and Cristiano, 1996). Bringing new products to market faster has become a strategic imperative in many markets (Zirger and Hartley, 1996). Many companies are adapting agile manufacturing practices. Agile manufacturing refers to the capability to quickly go from a set of novel customer requirements to a quality, finished product (Kleiner, 1997). Productivity, the dominant competitive paradigm prior to the late 1970's, has been replaced by quality (Haddad, 1996). Effective product development minimizes the resources (people, money, and time) required to provide an appropriate mix of product features, performance, quality, price, and availability to customers (Zirger and Hartley, 1996).

To be more competitive, many organizations are experimenting with a product development strategy called *concurrent engineering* (CE) (Salomone, 1995). CE is generally recognized as the practice of concurrently designing both the product and its downstream production and support processes in the early stages of design. In a concurrent engineering process, the downstream functions (e.g., manufacturing and support) are able to influence the design.

Historically, organizations have used a *sequential engineering* (SE) approach in which the product is designed and then its downstream manufacturing and support processes are designed. In a sequential engineering process, downstream functions have to influence product or system design through change order processes.

CE is believed to shorten product development time, increase product and process quality, and lower the cost of production (King and Majchrzak, 1996; Parsaei and Sullivan, 1993; Winner, Pennell, Bertrand and Slusarczyk, 1988). CE represents one of the most recent significant trends in new product development (Gerwin and Susman, 1996).

The effect of engineering methodology (EM), sequential or concurrent, on performance, time, cost, and other process variables is a major aspect of this research.

The use of multidisciplinary or cross-functional teams is a major tenet of CE (Winner et al., 1988). Using a team consisting of members representing all of the key functional organizations, especially marketing, engineering and manufacturing, has been identified with reduced development time (Zirger and Hartley, 1996). According to Zirger and Hartley (1996), teams, as compared to individuals, decrease time by facilitating communication, cross-functional cooperation and increasing goal congruence among the functional organizations. However, group dynamics research has found that as group size increases, interaction becomes more complex and the group may have difficulty reaching consensus (Shaw, 1981).

The terms *team*, *group*, and *working group* appear in the literature in a variety of contexts. Some authors differentiate between the terms. For example, Katzenbach and Smith in the *Wisdom of Teams* defined a team as follows (Katzenbach and Smith, 1993, page 45):

*“A team is a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable.”*

They then stated that working groups are not teams because there is no significant incremental performance need or opportunity that would require the group to become a team. Katezenback and Smith (1993) further refined the concept of teams into pseudo-teams, potential teams, real teams, and high-performance teams. This research, however, did not differentiate between various types of groups and teams. Therefore, the terms *team*, *group*, and *working group* will be used interchangeably herein.

The effect of group size (GS), specifically small three-person groups and large six-person groups, on performance, time, cost, and other process variables is another major aspect of this research.

Many tools are being developed to increase the concurrency of design by allowing teams of designers to remotely communicate on a network and share information in a common data base (Cleetus and Reddy, 1992). The importance of the development of tools to enable CE can be seen by the level of federal research funding allocated to CE tool development: \$60 million spent by Defense Advanced Research Projects Agency over a three-year period (Reddy, Wood and Cleetus, 1991). However, in some product classes, the use of CE tools has slowed the development process (King and Majchrzak, 1996).

Computer-supported cooperative work (CSCW) is a new field of research that draws together social scientists with system builders interested in developing a more-refined understanding of how people work together and make decisions (Galegher and Kraut, 1990). CSCW is a computer-assisted coordinated activity carried out by a group of collaborating individuals to solve problems and communicate (Baecker, 1993). The multi-user software supporting CSCW is called groupware. Herein, the term CSCW will be used when referring to theoretical issues. Groupware will be used when referring to the software used in this research. Decision-making ranks with innovation in the importance in the engineering design process (Siddall, 1972). Therefore, computer-supported cooperative work technology holds great potential for improving the design process.

The effect of computer-supported cooperative work technology (CSCW) on performance, time, cost, and other process variables is another major aspect of this research. New information technologies like CSCW have created a need to measure and evaluate system performance comprehensively. Kleiner (1997) proposed a generalizable framework for understanding, measuring, and evaluating performance within an information-based management system.

The theoretical basis of this research is sociotechnical systems theory. Sociotechnical systems (STS) theory suggests that personnel variables, like group size, must be considered along with technological variables, like the use of computer decision-making tools, to optimize the engineering design process. The top-down sociotechnical engineering systems approach to the design of organizations, work systems, jobs, and related human-machine, user-system, and human-environment interfaces is called macroergonomics (Hendrick, 1986; 1991; 1995).

This experimental research with field confirmation adopted a sociotechnical systems and macroergonomic view of the engineering design process. This means that the impact of both technological and personnel variables in the design of an engineering organization are considered. The following independent variables, each with two levels, were considered by this research:

- Engineering Design Methodology (EM): concurrent versus sequential engineering.
- Group Size (GS): large (six person) versus small (three person) groups.
- Computer-Supported Cooperative Work (CSCW): using versus not using computer-supported cooperative work technology (i.e., manual).

By experimental analysis of the main effects and interactions of these variables on design performance, process time, process cost, and member satisfaction, engineering organizations can develop strategies to become more competitive.

The following subsections elaborate on the independent variables manipulated in this research.

#### 1.1.1. Engineering Design Methodology

Dr. Nam P. Suh, the former assistant director for engineering of the National Science Foundation and professor at the Massachusetts Institute of Technology, stated that (Suh, 1990, p. 5):

*“Design, as the epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations.”*

The design process is often portrayed as a spiral or a helix (Suh, 1990) reflecting the iterative process of evolving a concept from a need, to requirements, to a design. Assumptions must be made and then verified.

There are two different approaches to design. In the *sequential engineering* (SE) or traditional approach, resources are focused on designing a product that will meet the customer’s need. Then, the design is evaluated for its manufacturability. After the manufacturing process has been designed, the design is evaluated for its supportability or maintainability. Then, the support processes are designed. Problems with manufacturability or supportability are referred to the design engineers for resolution.

In the *concurrent engineering* (CE) approach to design, manufacturing and support processes are designed at the same time the product is being designed. Manufacturing and support influence product design. While this approach would seem the most logical, it has only been used in the United States in the last ten years.

In the late 1980’s the Department of Defense formed a Technology Assessment Team to study Japanese manufacturing techniques. Their final report concluded that Japanese companies take half of the time that U.S. companies take to deliver major products like aircraft and automobiles by using a process that has come to be called concurrent engineering (Kelly and Nevins, 1989). The report stated the Japanese practice of concurrent engineering --- the

simultaneous design of the product and all supporting life-cycle processes - is a major factor in shortening the product-development cycle (Evanczuk, 1990). Concurrent engineering differs from the traditional sequential design process of designing the product, designing the manufacturing process, manufacturing the product, and finally, designing its support processes.

In 1988, the Department of Defense (DoD) tasked the Institute for Defense Analyses (IDA) to assess claims of improved product quality at lower costs and shortened product development time through the use of concurrent engineering. The final product of IDA's assessment was documented in Technical Report R-338, *The Role of Concurrent Engineering in Weapons System Acquisition*. An important contribution of this report was the following definition of concurrent engineering (Winner et. al., 1988, page 2):

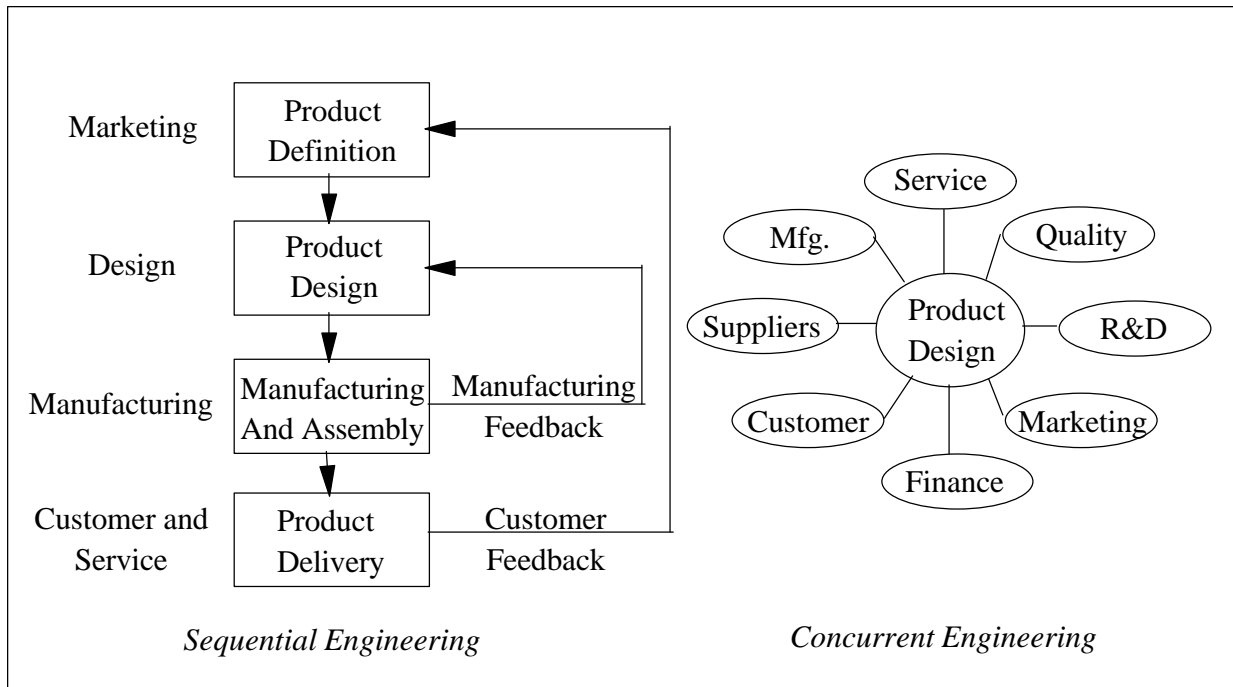
*“Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.”*

Others during the same time period offered similar definitions. The Pymatuning Group, Inc., under a contract from The Defense Advanced Research Projects Agency (DARPA) in 1988, defined CE to be the set of methods, techniques and practices that (Istvan, 1988):

- Cause significant consideration within the design phases of factors from later in the life cycle,
- Produce, along with the product design, the design of processes to be employed later in the life of the product,
- Facilitate the reduction of the time required to translate designs into the fielded products, and
- Enhance the ability of products to satisfy users' expectations and needs.

There are a number of terms that are often used synonymously with concurrent engineering. These terms more often represent the evolution of the concept in particular sectors of the market rather than a fundamental difference in the overall construct. Some of the terms frequently used are: “systems engineering” (1950's/60's), “simultaneous engineering” (automotive industry), “integrated product / process development” (Air Force), “producibility engineering” (manufacturing), “life-cycle engineering,” “design integrated manufacturing,” “design fusion,” “early manufacturing involvement,” “parallel engineering,” and “design in the large.” In Europe, “design for production” and “design for economic manufacture” have been used (Parsaei and Sullivan, 1993).

The integrated, concurrent design of the product and its manufacturing and logistic support processes is fundamental to concurrent engineering. Figure 1.1 compares a classical sequential approach to product development with a concurrent approach.



**Figure 1.1. A Comparison of Sequential and Concurrent Engineering Adapted from Carlson and Ter-Minassian (1997)**

The implementation of concurrent engineering employs a variety of tools, techniques, processes, many of which are product-specific. However, a key generic element of most implementations of concurrent engineering is “a reliance on multifunctional teams to integrate the designs of a product and its manufacturing and support processes” (Winner et. al., 1988). The size of these teams is a critical issue. Large teams consume resources at a faster rate; however, large teams bring more intellectual potential to the design challenge.

### 1.1.2. Group Size

Most of the work that people perform requires some degree of cooperation and communication with others, that is some kind of teamwork (Galegher and Kraut, 1990). *The Coming of the New Organization* by Peter Drucker in 1988 said business teams were the wave of the future (Drucker, 1988). The importance of teams as the future organizational unit was stated by Johansen in *Computer-Augmented Teamwork* as follows (Johansen, 1992, p. 14):

*“We are entering an age of organizational experimentation and redesign in which teams will be a basic - perhaps the basic - organizing unit. Flatter organizations will depend on teams to get things done; the remaining hierarchies will still provide basic business functions, but teams will be most important in most companies.”*

Katzenbach and Smith (1993) stated in *The Wisdom of Teams* that, “Teams outperform individuals acting alone or in larger organizational groupings, especially when performance requires multiple skills, judgments, and experiences” (p. 9). They further assert that teams should be the basic unit of performance for most organizations, regardless of size.

Teams formed to develop large, complex products (e.g., military systems) with members drawn from throughout the organization are called cross-functional teams. Cross-functional teams leverage the expertise of different areas on the design and definition of the product, foster communication, and facilitate achieving design consensus (Snoderly, 1992). Throughout the literature on concurrent engineering the terms cross-functional, multi-functional, and multidisciplinary are used somewhat interchangeably.

Multidisciplinary concurrent engineering teams make design and engineering decisions. Over thirty years ago Simon (1960) identified the stages in the decision making process to be intelligence, design, and choice. Simon further elaborated on design activities to include inventing, developing, and analyzing (Gallupe, DeSanctis and Dickson, 1988). Concurrent engineering teams formulate ideas, analyze them, and achieve consensus on final design decisions.

On complex products, the number of disciplines that could be represented on a concurrent engineering team can be quite significant. For example, a team might include members from electronic and mechanical design, software engineering, manufacturing, component reliability, maintainability, logistics support, life-cycle cost analysis, human factors, quality assurance, marketing, and management (Keller, 1992). The development of a complex product can require hundreds of people from various functional groups in an organization (Dierolf and Richter, 1990).

Given the need to have technical input from a large number of people, a key issue is the determination of the optimum number of people that should participate on the team. While more team members might imply additional resources such as ideas and information and leadership, Holloman and Hendrick (1971) found that groups of two were too small and groups larger than six did not produce improved enough results to warrant the additional costs of more members. This research, therefore, considered the effect of group sizes of three and six members on the engineering design process. Group size is an important variable in designing organizations that can have important ramifications on the cost and efficiency of an organization (Dierolf and Richter, 1990).

There have been a number of technology-based tools that have been developed to facilitate the work of groups. There are a number of terms in current use to describe the general area of computer-augmented teamwork. Computer-augmented teamwork is a perspective on computing and telecommunications based on the premise that the user is a collaborative work group rather than an individual - as in personal computing - or an aggregation of unallied users - as in time-share computing (Johansen, 1992). The use of this technology is a critical issue for management of engineering organizations. There can be high costs associated with its use; however, it may improve the efficiency and productivity of groups.

### 1.1.3. Computer-Supported Cooperative Work (CSCW)

Much of the literature concerned with technological support of group processes goes under the label of *group decision support systems* (GDSS). Yet, there is no consensus in the literature on what exactly constitutes a GDSS (Kraemer and Pinsonneault, 1990). Kraemer and

Pinsonneault (1990) defined and differentiated two broad types of technological support systems for group processes as: GDSS and *group communication support systems* (GCSS).

The following definition of a GDSS was developed by Gallupe (1992, p. 274):

*“GDSSs are defined as interactive, computer-based systems that assist groups in a variety of tasks such as generating ideas, formulating problems, analyzing information, and building consensus.”*

The following definition of a group communication support system (GCSS) is based on work by Kraener and Pinsonneault (1990, p. 198):

*“GCSS are information aids. They are systems that primarily support the communication process between group members, even though they might do other things as well. The main purpose of GCSS is to reduce communication barriers in groups.”*

Two terms will be used herein for use of computer technology to support the work of a group. Computer-Supported Cooperative Work (CSCW) is a very broad term that encompasses all of the terms cited. It is a rubric for interdisciplinary research across a range of disciplines including computer science, artificial intelligence, psychology, sociology, organizational theory, and anthropology (Greif, 1988). Groupware is the multi-user software supporting CSCW. The term has been defined as follows: (Johnson-Lenz, 1982, p. 47)

*“The intentional group processes and procedures to achieve specific purposes plus software tools designed to support and facilitate the group’s work.”*

The two terms are related as follows. CSCW is the emerging scientific discipline that guides the thoughtful and appropriate design and development of groupware (Greenberg, 1991)

#### 1.1.4. Sociotechnical Systems Theory / Macroergonomics

The term “sociotechnical system” was coined by Trist to describe the interrelatedness of the functioning of the social and technical subsystems of the organization and the relation of the organization as a whole to the environment in which it operates (Pasmore et. al., 1982). Sociotechnical systems theory is characterized by several core principles: joint causation, joint optimization, and joint design. Joint causation refers to the notion that the social and technical subsystems are both affected by the environment. Since both subsystems respond to causes in the environment, optimizing one suboptimizes the other. Joint optimization is therefore the goal. Joint design is the method by which joint optimization is achieved.

Three dimensions of the engineering design process were the focus of this research: (1) the overall engineering process methodology of concurrent engineering versus traditional, sequential engineering, (2) the personnel structure of those performing the design process based on group size, and (3) the technological structure supporting the design process as computer-supported cooperative work. The interrelationship of these variables as they might be jointly optimized was the goal of this research.

The consideration of an organizational system's social and technical subsystems in the design, implementation, and use of organizational systems has been called "macroergonomics" by its founder, Hal Hendrick (1985) and can be operationally defined as follows (Brown, Imada, Hendrick, and Kleiner, 1997):

*"Macroergonomics is concerned with the optimization of organizational and work system design through consideration of relevant personnel, technological, and environmental variables and their interactions."*

This dissertation applies macroergonomics and its STS theoretical underpinnings to the engineering design process to determine the optimum combination of technical considerations (e.g., engineering methodology and computer-supported cooperative work) and social considerations (e.g., group size) that will improve the performance and competitiveness of engineering organizations..

## **1.2. Problem Statement**

Competitive pressure causes companies to continually reexamine their processes for effectiveness, efficiency, productivity, and quality. The design process is particularly important because even though a relatively small cost is incurred during design, a high percentage of product life-cycle costs are committed early in the design process (Salomone, 1995).

Engineering managers deploy resources in order to achieve their mission. Resources can be directed at technological alternatives like the engineering process methodology used or the use of computer-support technology. Or alternatively, managers can direct resources at personnel alternatives like increasing the number of people on the project. Sociotechnical systems theory suggests that there is an optimum combination of personnel and technological alternatives that will optimize performance.

The problem statement of this research is: What is the relationship between the important design process, personnel, and technological issues that must be considered by management or management systems engineers responsible for organizations performing the design of complex systems? How do these issues interrelate? Is there an optimum combination of process, social and technical approaches that will maximize performance while creating a high quality of work life climate for employees?

## **1.3. Research Purpose**

The purpose of this research was to develop a better understanding of the relationships among technological and personnel variables. This information could then be used by engineering management or those responsible for the design of organizations to create higher-performing engineering design organizations. Specifically, this research considered two technological issues: (1) the overall design process methodology - concurrent engineering versus sequential engineering, and (2) whether to use or not use computer-supported collaborative work technology, and one personnel issue: (1) whether large teams of six persons would be more effective and efficient than small teams of three persons.

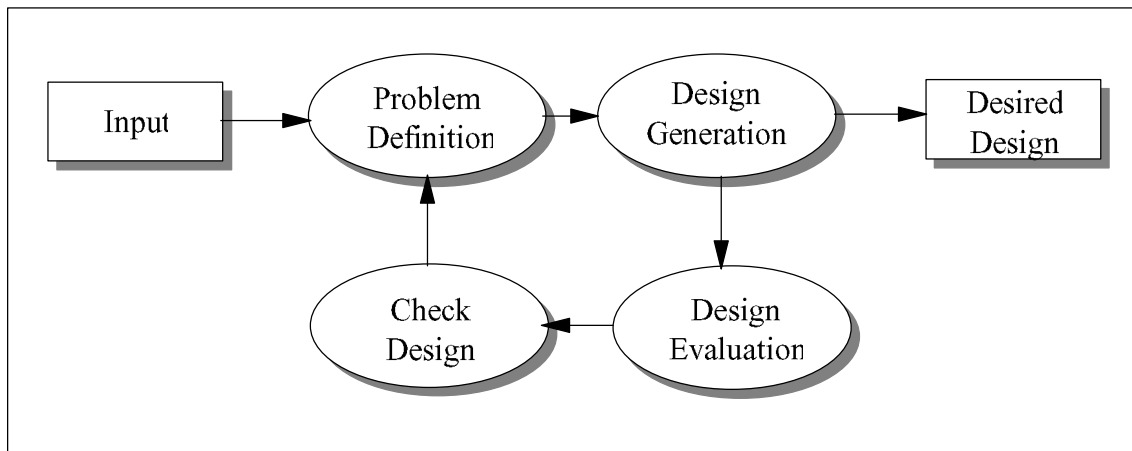


#### 1.4. Research Objectives

This research had a broad range of objectives. The first objective was to develop a theoretically-derived research base of knowledge to augment the existing body of anecdotal and research information related to concurrent engineering. Secondly, no known applications of CSCW have been researched in an engineering design environment. Therefore, an objective was to confirm the applicability of previous CSCW and groupware research to the engineering design environment. It was expected that this research would be able to identify other variables for future research that will increase the body of knowledge relating to the application of design process methodologies, teams, and CSCW. Finally, this research provided practical guidance to engineering design managers on effective and efficient ways to implement engineering design processes that would result in high performance and would be satisfying to group members.

#### 1.5. Conceptual and Research Models

Suh's (1990) conceptual model of the engineering design process is shown in Figure 1.2.

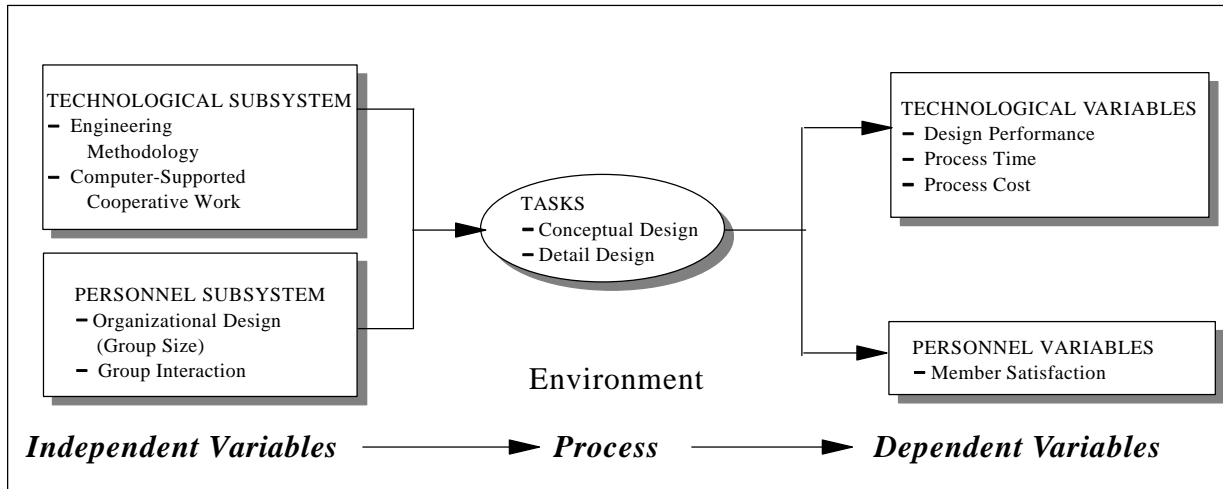


**Figure 1.2. Suh's Overall Conceptual Model of Design Process (1990)**

Suh (1990) defined the four components of the design process as: (1) problem definition from fuzzy sets of facts and myths into a coherent statement of the question, (2) the creative process of devising a proposed physical embodiment of solutions, (3) the analytical process of devising a proposed physical embodiment of solutions, and (4) the ultimate check of the fidelity of the design product to the original perceived needs.

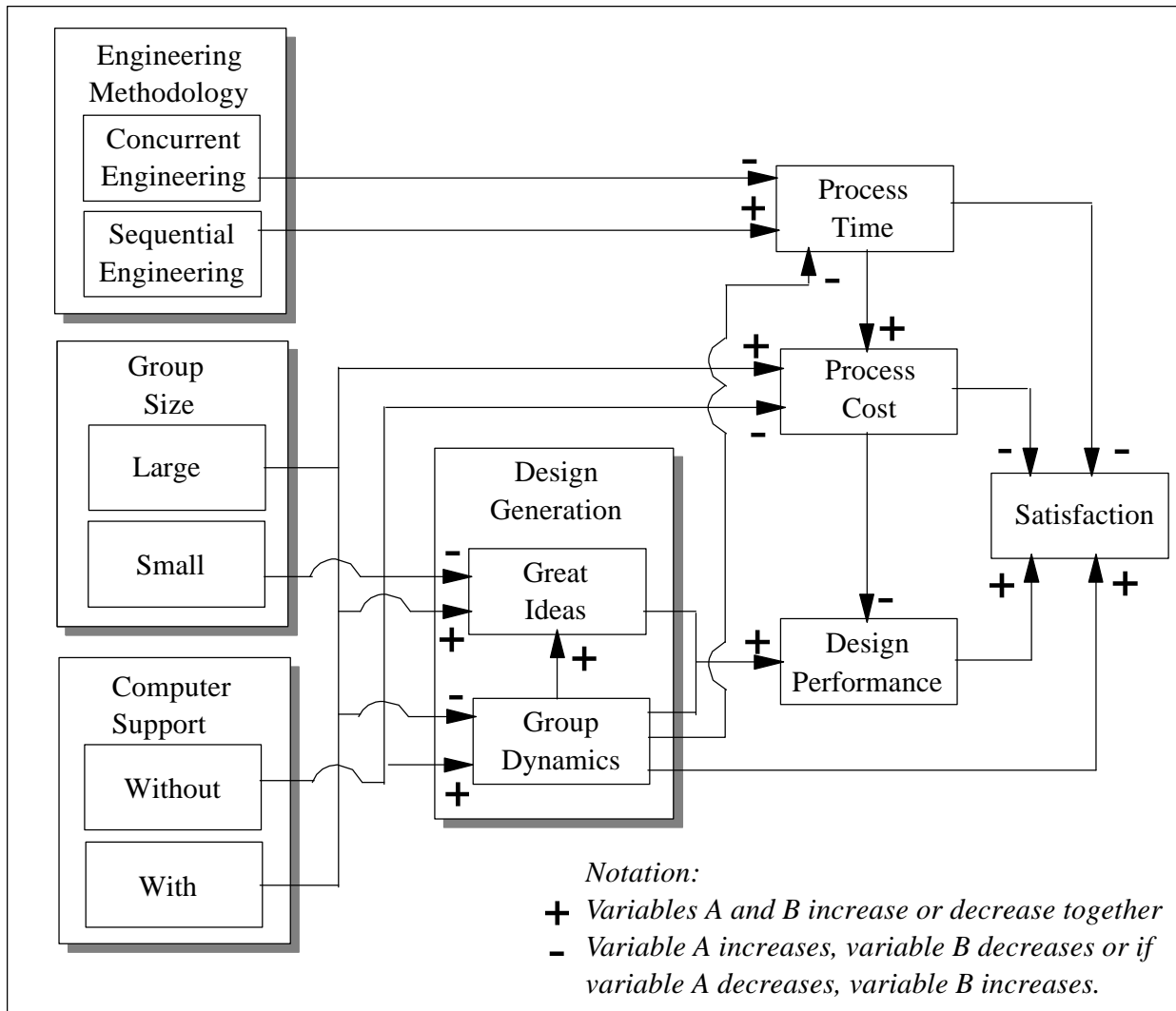
This research was primarily focused on the design generation component of the overall model. Suh's conceptual model of the design process is independent of process and socio-technical considerations. Since "design" does not specify whether it includes product and/or processes it is equally applicable to concurrent engineering or sequential design processes. Suh's model is also independent of technology used to define the problem, generate design alternatives, evaluate designs, and check them.

There are a number of conceptual models for depicting the relationship of the social subsystem, technical subsystem, and task to performance. The model used herein, Figure 1.3, is adapted from McGrath's work (McGrath and Hollingshead, 1994) and from Kraemer and Pinsonneault's conceptual model (Kraemer and Pinsonneault, 1990).



**Figure 1.3. Conceptual Model Adapted from McGrath (1994) and from Kraemer and Pinsonneault (1990)**

The research model, Figure 1.4, shows a causal diagram of the relationship among the major variables of this research. The model predicts that satisfaction will be positively effected by group dynamics and negatively effected of process time and cost. Design performance will be positively affected by the number of quality ideas generated and group dynamics while negatively affected by process cost. Process cost will increase with the use of computer-supported cooperative work technology and increased group size and will be positively related to process time. Process time will be increased by the use of sequential engineering and will be decreased with concurrent engineering. Excellent group dynamics will decrease process time. The use of computer-supported cooperative work technology will increase the number of quality ideas, has a negative impact on group dynamics, and will increase process cost. A greater group size will increase process cost and will increase the number of quality ideas.



**Figure 1.4. Research Model**

### 1.6. Research Questions and Hypotheses

The overall questions this research addresses and hypothesizes are discussed in this section. The following independent variables and their levels were used:

INDEPENDENT VARIABLE  
Engineering Methodology (EM):

LEVEL

Concurrent Engineering	CE
Sequential Engineering	SE

Group Size (GS):

Large Groups	LG
Small Groups	SG

Computer-Supported Cooperative Work Use (CSCW):

Computer Support	CS
No Computer Support	NS

The following dependent variables were considered by this research:

Design Performance (DP)  
Process Time (PT)  
Process Cost (PC)  
Member Satisfaction (MS)

### 1.6.1. Design Performance

*Research Question 1: How is design performance affected by engineering methodology, group size, and use of computer-supported cooperative work?*

#### *1.6.1.1. Engineering Methodology*

H<sub>0</sub>: Design performance is not affected by engineering methodology.

H<sub>1</sub>: The design performance of concurrent engineering groups will be greater than that of sequential engineering groups ( $DP_{CE} > DP_{SE}$ ).

There is a growing belief among practitioners and academicians that concurrent engineering positively impacts development time, product cost, and product quality (Liker et. al., 1996). Concurrent engineering is a very popular contemporary methodology because it has strong face validity and there are a large number of successful anecdotes reported in the literature.

#### *1.6.1.2. Group Size*

H<sub>0</sub>: Design performance is not affected by group size.

H<sub>1</sub>: The design performance of large groups will be greater than small groups ( $DP_{LG} > DP_{SG}$ ).

Steiner's theory of group productivity states that performance should increase with group size when the task is additive or disjunctive (Steiner, 1972). Social facilitation research has shown that the presence of others can improve a person's performance for easy tasks and hinder performance for more difficult tasks (Zajonc, 1965). Large groups have more knowledge and experiential resources to apply to design conception and design problem solving. Other process gains expected by large groups are synergy and better evaluation of alternatives.

### 1.6.1.3. *Computer-Supported Cooperative Work*

H<sub>0</sub>: Design performance is not affected by computer support.

H<sub>1</sub>: The design performance of computer-supported groups will be greater than non-computer-supported groups ( $DP_{CS} > DP_{NS}$ ).

Performance should be better in computer-supported groups because of task focus, higher quality communication, better decision quality, and greater level of effort put into the decision process (Kraemer and Pinsonneault, 1990). Computer-supported cooperative work technology provides a framework of tools that will allow engineers to perform complex design tasks more efficiently (Salomone, 1995).

The Fellers laboratory experiment showed that groups generated significantly more ideas, different ideas, ideas of higher total quality, and more good ideas (as rated by expert judges) and were more satisfied with the group idea-generation process when given computer support (Bostrom, Watson and Over, 1992). Electronic brainstorming was not only the most productive technique in the number of unique ideas generated, compared to traditional and nominal brainstorming, but the most satisfying (Gallupe, 1992).

Given that engineering design could be defined as a difficult task, Gallupe, DeSanctis and Dickson (1988) have shown in their research that the benefits of CSCW are more detectable for relatively difficult tasks. And, given that four studies of computer supported groups showed that they had a higher degree of consensus (McGrath and Hollingshead, 1994), design performance should be better with CSCW.

### 1.6.2. Process Time

*Research Question 2: How is process time affected by engineering methodology, group size, and computer-supported cooperative work?*

#### 1.6.2.1. *Engineering Methodology*

H<sub>0</sub>: Process time is not affected by engineering methodology.

H<sub>1</sub>: The process time of sequential engineering groups will be greater than concurrent engineering groups ( $PT_{SE} > PT_{CE}$ ).

In sequential product development projects, each stage of the project is performed sequentially with the functional groups “handing-off” the project to one another after an extensive stage-gate evaluation process. Overlapping development activities traditionally performed sequentially, such as product and process design, will reduce development time (Zirger and Hartley, 1996). Many companies have reported between 30% to 70% reductions in total development time using concurrent engineering (Salomone, 1995).

#### 1.6.2.2. *Group Size*

H<sub>0</sub>: Process time is not affected by group size.

H<sub>1</sub>: The process time of large groups will be greater than small groups ( $PT_{LG} > PT_{SG}$ ).

In general, the larger the group the greater the difficulty in obtaining consensus requiring more time (Shaw, 1981). Large groups may also expend time overcoming other process losses like socializing, coordination problems, and competition for available speaking time.

#### *1.6.2.3. Computer-Supported Cooperative Work*

H<sub>0</sub>: Process time is not affected by computer support.

H<sub>1</sub>: The process time of computer-supported groups will be greater than non-computer-supported groups ( $PT_{CS} > PT_{NS}$ ).

Computer support can increase or decrease time based on the task, the participation level, and the degree of group focus (Kraemer and Pinsonneault, 1990). Given the difficulty of the design task and the overall unfamiliarity of the subjects with computer-support tools, the process time is expected to be greater using computer-support tools.

#### 1.6.3. Process Cost

*Research Question 3: Is process cost affected by engineering methodology, group size, or computer-supported cooperative work?*

##### *1.6.3.1. Engineering Methodology*

H<sub>0</sub>: Process cost is not affected by engineering methodology.

H<sub>1</sub>: The process cost of concurrent engineering will be less than sequential engineering ( $PC_{CE} < PC_{SE}$ ).

Process cost differences between sequential and concurrent engineering are expected to be proportional to the impact of these processes on time. Therefore concurrent engineering should have much lower process cost.

##### *1.6.3.2. Group Size*

H<sub>0</sub>: Process cost is not affected by group size.

H<sub>1</sub>: The process cost of large groups will exceed that of small groups ( $PC_{LG} > PC_{SG}$ ).

The process cost of large groups, based on person-hours expended multiplied by a labor rate, is expected to cause large groups to be more expensive than small groups.

##### *1.6.3.3. Computer-Supported Cooperative Work*

H<sub>0</sub>: Process cost is not affected by computer support.

H<sub>1</sub>: The process cost of computer-supported groups will be greater than non-computer-supported groups ( $PC_{CS} > PC_{NS}$ ).

The cost of tools and equipment is expected to cause the process cost of computer-supported groups to exceed that of non-computer-supported groups. Also, since computer-supported groups are expected to require more time, the process cost will be greater.

#### 1.6.4. Member Satisfaction

*Research Question 4: Is the satisfaction of group members affected by engineering methodology, group size, or computer-supported cooperative work?*

##### *1.6.4.1. Engineering Methodology*

H<sub>0</sub>: Group member satisfaction will be affected by engineering methodology.

H<sub>1</sub>: There will be no significant difference in member satisfaction in either concurrent or sequential engineering.

Given an unlimited amount of time to complete the experiment, there is no reason to expect that group member's satisfaction would be influenced by engineering methodology.

##### *1.6.4.2. Group Size*

H<sub>0</sub>: Group member satisfaction will be affected by group size.

H<sub>1</sub>: There will be no significant difference in member satisfaction in either large or small groups.

Given an unlimited amount of time to complete the experiment, there is no reason to expect that group member's satisfaction would be influenced by group size.

##### *1.6.4.3. Computer-Supported Cooperative Work*

H<sub>0</sub>: Group member satisfaction will be affected by computer support.

H<sub>1</sub>: There will be no significant difference in member satisfaction.

Given an unlimited amount of time to complete the experiment, there is no reason to expect that group member's satisfaction would be influenced by computer support.

#### 1.6.5. Optimum Combination

*Research Question 5: Is there an optimum combination of engineering methodology, group size, and computer support that creates the greatest technical and social outcome?*

H<sub>0</sub>: There is no optimum condition.

H<sub>1</sub>: Non-computer-supported, large, concurrent engineering groups will be the optimum condition.

If the prior hypotheses are supported, then the optimum condition would be large, non-computer-supported, concurrent engineering groups.

Table 1.1 summarizes the hypotheses of this research.

	Engineering Method		Group Size		Computer Support	
	<i>Concurrent</i>	<i>Sequential</i>	<i>Large</i>	<i>Small</i>	<i>Support</i>	<i>Non-supported</i>
<b>Design Performance</b>	Higher	Lower	Higher	Lower	Higher	Lower
<b>Process Time</b>	Lower	Higher	Higher	Lower	Higher	Lower
<b>Process Cost</b>	Lower	Higher	Higher	Lower	Higher	Lower
<b>Member Satisfaction</b>	Same	Same	Same	Same	Same	Same

**Table 1.1. Overview of Research Hypotheses**

## 1.7. Premises and Delimitations

Premises form the basis upon which this research rests. Delimitations define the scope of the research.

### 1.7.1. Premises

- There is little formal research to substantiate the value of concurrent engineering.
- Continued rapid growth in the body of knowledge will challenge management to develop effective ways to identify and extract relevant knowledge and apply it to the engineering design process. The employment of efficiently sized teams will be the most effective way to tap into the collective knowledge base.
- The capability and sophistication of computer technology to support work groups will continue to increase.
- Previous computer-supported cooperative work research has not addressed tasks related to the design process.
- Improper design of the design process may be manifested in poor product design resulting in decreased international competitiveness and loss of value to society.
- This research assumes that the use of students as subjects is generalizable to the professional engineering design community.
- This research assumes that the task used herein is representative of engineering tasks in industry.

### 1.7.2. Delimitations

- This research will not consider contextual variables related to the composition of a group with respect to any sociological or psychological variables like: team member gender, experience level, abilities, motives, personal preferences, level of team member familiarity or age.
- This research will not study the usefulness or utility of a particular computer-supported cooperative work technology product (i.e., groupware). In other words, this research will not consider specific hardware and/or software alternatives as an independent variable.
- This research assumes that the engineering design process at the level researched herein is generalizable to more complex products and systems.



## **1.8. Desired Outputs and Outcomes**

Desired outputs of this research were:

- A description of how sequential and concurrent engineering methodologies, large and small groups, and the use or not use of computer-supported cooperative work impact design performance.
- A description of how sequential and concurrent engineering methodologies, large and small groups, and the use or not use of computer-supported cooperative work impact process time.
- A description of how sequential and concurrent engineering methodologies, large and small groups, and the use or not use of computer-supported cooperative work impact process cost.
- A description of how sequential and concurrent engineering methodologies, large and small groups, and the use or not use of computer-supported cooperative work impact the satisfaction of group members with the design process.

Desired outcomes of this research are:

- A scholarly research assessment of the relationship among personnel, technological and process variables of the engineering design process.
- Identification of issues that need to be considered by management or those responsible for the design of engineering design processes.
- An assessment of the impact of the use of computer-supported cooperative work technology implemented in a design process.
- A solid research foundation for concurrent engineering to augment the large existing body of anecdotal information documented in practitioner literature.
- Information that contributes to the emerging models and understanding of groups using computer-supported cooperative work technology;
- Better designed engineering design processes resulting in higher performance and greater member satisfaction with the process.

## **1.9. Justification for this Research**

Design facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations. Poor design practice results in high cost and long delivery times, which may be devastating to a firm or a nation depending on those products (Suh, 1990).

The following statements from Parsaei and Sullivan's (1993) text, *Concurrent Engineering*, document the significance of product design:

- Boothroyd cites published reports from Ford Motor Company which estimate even though product design accounts for only 5% of total product cost, 70% of the cost is influenced by the design.
- It is believed the 40% of all quality problems can be traced to poor design.
- Suh (1990) believes that as much as 70-80% of manufacturing productivity can be determined at the design stage.
- Gatenby and Foo estimate that an even higher percentage (from 80 to 90%) of the total life-cycle cost of a product is determined during the design phase.
- An observable statement of a manufacturing executive quoted in a prestigious paper: 'designers make million-dollar decisions every minute without ever knowing it.'

Clearly the value of designing good engineering design processes with appropriate consideration of both technological and personnel subsystems is substantial.

Management systems engineering is the application of engineering design principles and processes to a management system. Management systems engineers need to be able to design organizations that will be high-performing and will be satisfactory to its members. Specifically, management systems engineers need to understand the relationships among process, personnel, and technological variables of the engineering design process. This research adds to the body of practical and theoretical knowledge available to practicing management systems engineers and the profession of industrial engineering.

## 2. Review of the Body of Knowledge

### 2.1. Introduction

This chapter provides a review of the literature and body of knowledge of a number of topics that frame the domain of this research. The basis of this research is *sociotechnical systems theory* (STS). Interest in sociotechnical system methods has grown almost geometrically since the initial classic studies of the British coal mining industry were first published in 1951 (Pasmore, Francis and Haldeman, 1982). According to Pasmore (1982) organizations are made up of *people* that produce products or services using *technology*, and that each affects the operation and appropriateness of the technology as well as the actions of the people who operate it. Sociotechnical systems theory simply states that performance is a function of the joint operation of the personnel and technological systems (Herbst, 1974).

The application of sociotechnical systems theory to the top-down design of organizational and work system structures, and to related jobs and human-machine, human-environment, and user-system interfaces has been conceptually defined as *macroergonomics* (Hendrick, 1995). Hendrick (1995) identified four major sociotechnical system elements of macroergonomics as: the personnel subsystem, technological subsystem, organizational design, and the external environment. This review of the literature considers each element in the context of this research.

The domain of this research is engineering design. Engineering design is a purposeful activity directed toward the goal of fulfilling human needs, especially those that can be met by the technological factors of our culture (Asimow, 1962). Design facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs (Suh, 1990). The Accreditation Board for Engineering and Technology provided the following definition of engineering design (Ertas and Jones, 1993, p. 2):

*“Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation.”*

Engineering design involves decision-making. Decision-making ranks with innovation in importance in the engineering design process (Siddall, 1972). The literature in the decision-making area and the theory of design is reviewed in the context of this research.

Two of the independent variables of this research, *engineering methodology* and *computer support* are considered part of the technological subsystem of macroergonomics. The literature related to the two engineering methodologies, sequential and concurrent engineering, is provided.

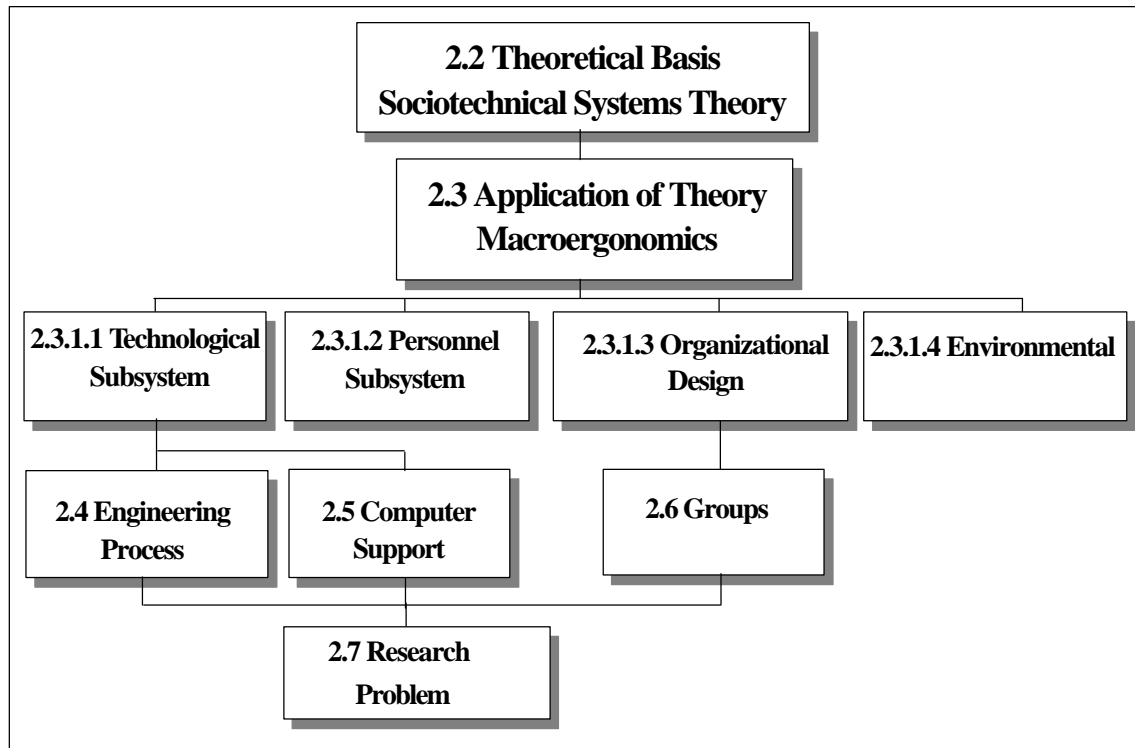
Computer support of the engineering process is one of the most significant new technologies affecting engineering design (Ertas and Jones, 1993). Computer support encompasses a number of computer tools that assist designers in a variety of tasks such as

generating ideas, formulating problems, analyzing information, building consensus, and communicating the design to others. This chapter reviews the literature in this area.

The design of complex systems today involves human interaction among engineers with various backgrounds from various disciplines organized into teams (Dierolf and Richter, 1990). The use of teams is a component of the organizational design element of macroergonomics. Few designs are truly done by individuals. Designers continuously exchange information with other persons even if not in teams (Ehrlenspiel and Dylla, 1993). The role of designers is a central, integrative one, for they must interact with people in virtually every part of the company, as well as people outside. Often it is not possible to identify an individual as “the designer” and the design must be regarded as a team or company activity (Taylor, 1993). The literature relating to the performance of individuals versus groups in the engineering design domain is provided.

The literature on various theories of groups is reviewed. There are a number of different types of groups or teams in the engineering design domain. The literature on the various types is provided. Given that in today’s environment engineering design is performed by teams, the size of the team, the third independent variable of this research, is an important issue. The benefits of a larger team in terms of greater sum total of knowledge and information have to be considered in terms of its greater cost in manpower and the phenomena of “diminishing returns” (Hare, 1976). The literature on previous research on group size is provided.

Previous macroergonomic studies on these variables are provided as well as other empirical studies. Given the contemporary interest in these areas, information from the practitioner literature is provided in addition to that found in the scholarly literature. The organization of the material to be presented is shown in Figure 2.1.



**Figure 2.1. Organization of Chapter 2**

## **2.2. Theoretical Basis --- Sociotechnical Systems Theory**

The theoretical basis for this research is sociotechnical systems (STS) theory. Sociotechnical theory and work of the “sociotechnical school” centered around the Tavistock Institute, which was founded in London in 1946. The Tavistock Institute was set up for the specific purpose of actively relating the psychological and social sciences to the needs and concerns of society (Trist, 1993b). Tavistock was to be a bridge between academic research and industry, making practical and accessible the best ideas to come out of academia to public and private organizations (Pasmore and Khalsa, 1993).

Studies by Trist and others from Tavistock on the British coal mining industry gave birth to the concept of sociotechnical systems. The sociotechnical systems approach considered an organization to be composed of a technological system, including both the tools and the knowledge needed to perform the work, and a personnel system, which resulted from the combination of people, relationships, culture, management methods, and experiences of working in the organization (Pasmore and Khalsa, 1993).

Today, sociotechnical system interventions are organizational development techniques whose objective is the optimization of the relationship between the personnel or human systems of the organization and the technology used by the organization to produce output (Pasmore and Sherwood, 1978), or large scale change (Kleiner, 1996).

### 2.2.1. Historical Background

The term “sociotechnical system” was coined by Trist to describe the interrelatedness of the functioning of the personnel and technological subsystems of the organization and the relation of the organization as a whole to the environment in which it operates (Pasmore et. al., 1982). The basic concepts can be traced back to a paper by Trist and Bamforth in 1951 on the social and psychological consequences of the longwall method of coal-mining (Herbst, 1974).

Mechanization was introduced into the coal-mining industry to increase productivity. Prior to mechanization each man carried out the entire task of mining. After mechanization the men were organized into teams of forty to fifty men, each working on a single task (Herbst, 1974). Groups of workers optimized conditions for themselves, creating and passing on bad conditions to work groups responsible for subsequent tasks. This process created interpersonal and intergroup conflict that contributed to a low level of performance.

Different mines utilized a variety of technical and work arrangements to accomplish similar tasks. Even when using similar technologies, different social arrangements within the workplace produced profoundly different economic and human results (Pasmore and Khalsa, 1993). According to Pasmore (1993, p. 554):

*“The observation of different work-group configurations around similar technologies led to the postulation by the researchers that technology did not strictly dictate social arrangements and their consequences; instead, many social arrangements were possible (“equifinality,” in systems terminology) concerning the scope of roles, the nature of pay, the role of management, methods of team selection, team size, and the degree of involvement in decision making and change by the workers.”*

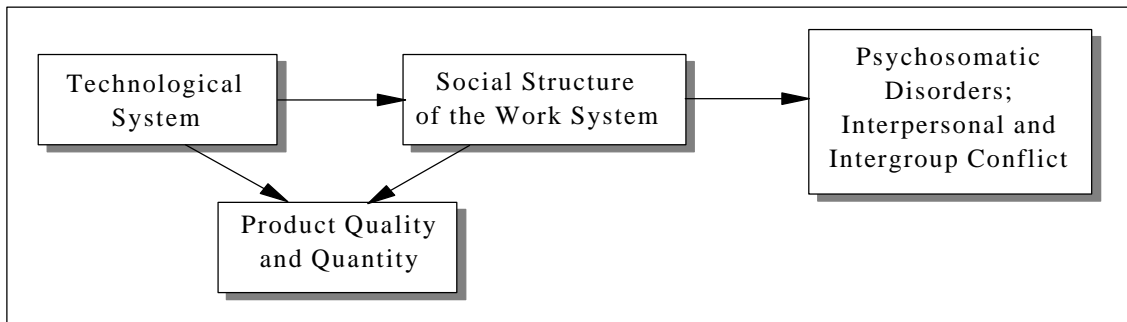
Originally, the formulation of personnel and technological relations had been made in terms of obtaining the best match, or “goodness of fit,” between the two (Trist, 1993). The full theoretical formulation of sociotechnical systems theory was not completed until Fred Emery joined Trist at Tavistock (Pasmore and Khalsa, 1993). The principle of *joint optimization of the personnel and technological systems* offered by Emery in 1959 stated that an organization will function optimally only if the personnel and technological systems of the organization are designed to fit the demands of each other and the environment (Pasmore et. al., 1982).

The technological and personnel systems are independent of each other, the former following the laws of physics, and the later following the laws of the human sciences (Trist, 1993). They require each other for the transformation of inputs into outputs. The technological and personnel systems relationship represents a coupling of dissimilars that can only be jointly optimized. According to Pasmore (1993, p. 555):

*“An excellent technical system would perform poorly if it created undue hardships for people, and a solid supportive social system could not compete if it utilized technologically disadvantaged work processes.”*

Attempts to optimize for either the technological or personnel system alone will result in the suboptimization of the sociotechnical whole according to Trist (1993).

An analytical model of this concept is provided in Figure 2.2.



**Figure 2.2. Analytical Model of Sociotechnical Systems (Adapted from Trist, 1993)**

According to Pasmore (1993), sociotechnical systems caught on in part because it worked for everyone, managers and workers alike; higher performance was associated with improved satisfaction and quality of work life.

### 2.2.2. Concepts of Sociotechnical Systems Theory

The following sections expand upon the major concepts of STS, namely the personnel system, the technological system, the environment, and self-regulating work groups.

#### *2.2.2.1. Personnel System*

People and the relationships among them comprise the personnel system of an organization (Trist and Bamforth, 1951). The aspects of people that are of relevance to the personnel system are not hands, feet, and muscles, so much as attitudes, beliefs, and feelings (Trist, Susman and Brown, 1977). According to Pasmore (1988, p. 25):

*“The social system encompasses individual attitudes and beliefs; the implicit psychological contracts between employees and employers; reactions to work arrangements, company policies, and design features; relationships between groups, among group members and between supervisors and subordinates; cultures, traditions, past experiences and values; human capacities for learning and growth as well as for sabotage and collusion; power and politics; individual personalities and group norms; the potential for motivation or alienation; for loyalty or dissension; for cooperation or conflict; and remarkable, uniquely human emotions such as love, hate, greed, charity, anger, joy, fear, pride, devotion, jealousy, compassion, and excitement.”*

According to Cherns (1978 and 1987), if a personnel system is to survive it must perform the function of Parson’s four subsystems. The first subsystem is the Goal Attainment Subsystem. This subsystem is the set of structures which allows a system to produce goods and services. The second subsystem is the Adaptation Subsystem which is made up of the various capacities with which the organization and its parts deal with environmental and internal turbulence. The third subsystem is the Latency or Pattern Maintenance Subsystem. This subsystem maintains the

equilibrium between member's roles within the organization and their roles outside the organization. The fourth subsystem is the Integration Subsystem through which organizations act with unity of effort. Organizational designers that do not take these subsystems into account will find their designs thwarted in negative ways.

Sociotechnical systems theory contends that identifying the needs that people bring with them to the workplace, and incorporating means of meeting those needs through the design of the technology and the work itself, is the surest way to achieve organizational goals (Pasmore et. al., 1982).

#### 2.2.2.2. *Technological System*

The technological system of an organization consists of the tools, techniques, procedures, skills, knowledge, and devices used by members of the personnel system to accomplish organizational tasks (Trist and Bamforth, 1951). Technological systems can be arrayed over a geographical area and joined together by the timing and movement of raw materials and information (Trist et. al., 1977). According to Trist (1977), industrial and production engineers are generally responsible for the design of technological systems and use criteria such as minimizing cost and throughput time and maximizing productive capacity.

Emery and other Tavistock researchers defined a number of important features of the technological system, originally in a paper published by Emery in 1959 (Emery, 1993). Some of those features include:

1. The characteristics of the material as it relates to variation in labor requirements.
2. The level of mechanization or automation.
3. The grouping of unit operations into production phases.
4. The degree of centrality of the different production operations.
5. The maintenance operations needed to maintain production.
6. The nature of supply operations as it relates to variation in the environment.
7. The spatio-temporal distribution of machines, workers, and processes.
8. The physical work setting in terms of factors such as temperature, light, noise, etc.

Sociotechnical systems theorists contend that organizational designers constrain themselves unnecessarily in the choices that they make regarding the technological system, and tend to overlook opportunities to redesign technologies to meet the needs of people (Pasmore et. al., 1982).

#### 2.2.2.3. *Environment*

Sociotechnical systems theory regards organizations as open systems that exist through regular commerce in products or services with other enterprises, institutions and persons in its external social environment (Emery, 1993). According to Emery (1993), the technological system functions as a major boundary condition of the personnel system in mediating between the ends of an enterprise and the external environment.

Emery and Trist recognized that the environmental contexts in which organizations exist are themselves changing, at an increasing rate, and towards increasing complexity (Emery and



Trist, 1965). The key components of the environment are customers (whose demands the organization must seek to satisfy) and competitors (who are also vying to serve the same demands) (Shani, Grant, Krishnan and Thompson, 1992). As competition intensifies and customers become more sophisticated and fickle, the external environment becomes less stable and more complex, according to Shani, et. al. (1992).

The task environment of a sociotechnical system are those external elements that are relevant to the setting and achievement of system goals (Cummings, 1978). For lower level organizations, the environment could consist of other organizational units internal to the total organization. For high-level units, the environment may be mainly external to the organization.

#### 2.2.2.4. *Self-Regulating (Autonomous) Work Groups*

Self-regulating work groups are an attempt to design effective relationships between the personnel and technological systems and between the work system and its task environment (Cummings, 1978). Autonomous work groups are groups of multiskilled workers which possess all of the skills essential to the performance of a particular, “whole” task, and which decide on its own allocation of labor, and sometimes on other matters, such as internal leadership (Kelly, 1978). According to Pasmore and Khalsa (1993), groups played a figural role in Trist’s work both as a subject of research and a method of working with others. Trist valued groups as often untapped sources of productivity and fulfillment.

Trist’s work with groups predated the British coal mining studies. The idea that a group could be self-regulating at work derived initially from proving that even groups of seriously ill psychiatric patients were capable of self-regulation in their treatment.

Sociotechnical systems theorists created autonomous work groups to control “variances” as near to their point of occurrence as possible (Kelly, 1978). By transitioning from the individual to the group as the crucial unit of analysis and action, variances in production could be evenly distributed among its members, according to Kelly (1978). Trist stated that groups had a superior capability to flexibly deploy their human and technological resources (Trist et. al., 1977).

The use of autonomous work groups has almost become synonymous with sociotechnical systems since the application of autonomous work groups have dominated both scientific and popular writings (Cummings, 1986). According to Cummings (1983), autonomous work groups will most likely succeed in situations featuring high levels of technological interdependence and uncertainty and a lack of strong norms favoring individualistic, professional forms of working, such as those found in hospitals and settings employing “high technology.”

Not all scholars have embraced the extensive use of autonomous work groups advocated by the sociotechnical systems theorists. For example, Hackman writes (p. 81):

*“But I can find neither in the research literature nor in my own experience justification for opting for groups as the design device of choice on an almost automatic basis, as seems to be done in a very large number of sociotechnical change projects.”*

The growing use of self-managed work groups in organizations suggests that they are a unique and viable alternative to traditional forms of work design. However, Cummings (1977) cautions that their popularity may lead organizational members to overestimate the general

applicability of self-regulating groups or to underestimate the conditions necessary for their implementation and continued effectiveness.

### 2.2.3. Principles of Sociotechnical Systems Design

Cherns (1987) developed a set of nine principles for organizational designers to use that operationalizes the concepts of sociotechnical systems theory. He suggested that these are a checklist, not a blueprint for designers to consider. An overview of the principles are provided below:

#### *Compatibility*

The process of design must be compatible with its objectives; meaning, for example, that if a participative personnel system is desired, then the people in the organization should be given an opportunity to design the organization.

#### *Minimal Critical Specification*

No more should be specified than is absolutely essential. For example, it may be necessary to be precise about what has to be done, but not necessarily how it is to be done.

#### *The Socio-Technical Criterion*

Variances that cannot be eliminated, must be controlled as near to their point of origin as possible.

#### *The Multifunctionality Principle --- Organism vs. Mechanism*

Functions can be performed in different ways by using different combinations of elements because there are several routes to the same goal.

#### *Boundary Location*

Boundaries should be located so as to not interfere with desirable sharing of knowledge and experience. Boundary maintenance is the preferred role of the leader of a well-designed organization.

#### *Information Flow*

Information systems should be designed to provide information in the first place to the point where action on the basis of it will be needed.

#### *Support Congruence*

The personnel support system (e.g., compensation) should be designed so as to reinforce the behaviors the organizational design is designed to elicit.

#### *Design and Human Values*

The objective of organizational design should be to provide a high quality of work. Quality is a subjective phenomenon. Not everyone wants responsibility, variety, and growth.

### *Incompletion*

As soon as a design is implemented there is a need for redesign. The multifunctional, multidisciplinary team required for design is needed for its evaluation and review.

#### 2.2.4. Case Studies

Pasmore, Francis and Haldeman (1982) reviewed 134 sociotechnical systems experiments in 1982 and found that while experiments have been extremely successful overall, the number of experiments involving technological innovation or change was relatively small. Their study showed that certain elements of sociotechnical systems theory were applied more often than others as shown in Table 2.1.

<b>Percent of Studies Using this Feature</b>	<b>Feature</b>
53	Use of autonomous work groups.
40	Emphasis on technological skill development.
22	Formation of an action group to recommend system changes.
21	Alterations to the reward system to make it consistent with sociotechnical system philosophy.
16	Self-inspection of work quality of operators.
16	Technological changes to support desired personnel system.
16	Use of a team approach to work (in contrast to the autonomous work group approach above, this method involves the formation of teams which remain under direct supervision and in which members do not rotate jobs).
14	Facilitative leadership (involving explicit managerial training or selection activities aimed at improving problem solving and interpersonal skills).
12	Performance of maintenance by operators.
9	Minimal critical specification.
9	Feedback on performance (regular and direct).
9	Direct interface with customer or user by operator.
8	Self-supply of materials by operators.
7	Managerial information for operators.
6	Self-selection of peers by group members.
4	Status equalization between management and operators.
4	Pay for learning new tasks.
3	Peer review by group members

**Table 2.1. Feature Use in Sociotechnical Experiments (Adapted from Pasmore, Francis and Haldeman, 1982)**

### 2.2.5. Summary of Sociotechnical Systems Theory

The following summarizes the differences between the traditional and sociotechnical view of organizations (Banner and Gagne, 1995):

#### Traditional View

People are extensions of machines  
People as expendable spare parts  
Maximum task breakdown  
Narrow skills  
Autocratic management style  
Competition

#### Sociotechnical View

People are complements to machines  
People as a resource to be developed  
Optimum task grouping  
Multiple broad skills  
Participative management styles  
Collaboration

According to Banner and Gagne (1995), a literature review of sociotechnical systems revealed a bias toward variety, challenging jobs, social support, collaboration and recognition, whole jobs (rather than division of labor), minimized external controls, and performance feedback on a timely basis.

Most sociotechnical system experiments have been undertaken primarily in blue-collar industrial settings (Pasmore et. al., 1982). However, Beekun's meta-analysis of 17 sociotechnical studies showed that white-collar worker's productivity increases matched those of blue-collar workers (Beekun, 1989). Kleiner (1996) produced large scale change in industry, government and academia.

In summary, the sociotechnical systems approach acknowledged that demands from the external environment can compel changes in either the technological or the personnel system. Furthermore, the two systems are inextricably intertwined. Therefore, there must be a synchronicity between the two systems in order for optimal work effectiveness to be achieved (Banner and Gagne, 1995).

### **2.3. Application of Theory --- Macroergonomics**

Macroergonomics is concerned with the optimization of organizational and work system design through consideration of relevant personnel, technological, and environmental variables and their interactions (Brown, Imada, Hendrick, and Kleiner, 1997). Macroergonomics involves a systematic analysis of the key characteristics of the technological system, personnel system, and environment. Once the characteristics of the over-all work system have been determined, they, in turn, prescribe the characteristics that need to be micro-ergonomically designed into the individual jobs, specific work processes, and related human-machine and user system interfaces (Hendrick, 1995). The result, according to Hendrick (1995), is a fully harmonized work system at both the macro- and micro-ergonomic level. Kleiner (1996b) demonstrated how this balance helps to manage extreme intervention approaches such as reengineering and deengineering.

### 2.3.1. Macroergonomic Subsystems

Consistent with STS theory, macroergonomics assumes the organization is composed of: (1) the technological subsystem, (2) the personnel subsystem, (3) the environmental subsystem, and (4) the organizational design subsystem. The following subsections elaborate on these subsystems as they are presented in the macroergonomics literature.

#### 2.3.1.1. *Technological Subsystem*

The design of the technological subsystem defines the tasks that are to be performed. According to Hendrick (1986), technology has been operationally defined in several ways: mode of production, strategies for reducing technological uncertainty, and the knowledge-based concept of technology of Perrow.

Perrow defined technology as the action that one performs upon an object in order to change that object (Perrow, 1967). Perrow's definition of object is quite broad. It can be a living being, human or otherwise, a symbol, or an inanimate object. For example, people are the object in people-changing or people-processing organizations. Symbols are the objects in banks, advertising agencies, and some research organizations. Given that this action requires some form of knowledge, technology can be categorized by the required knowledge base. Perrow identified two underlying dimensions of knowledge-based technology: task variability, and task analyzability. Task variability relates to the number of exceptions encountered in one's work. Task analyzability refers to the type of search procedures one has available for responding to task exceptions. Table 2.2 shows the result of dichotomizing these variables into four cells.

	<b>Task Variability</b>	
<b>Problem Analyzability</b>	<b>Routine with Few Exceptions</b>	<b>High Variety with Many Exceptions</b>
<b>Well Defined and Analyzable</b>	Routine	Engineering
<b>Ill Defined and Not Analyzable</b>	Craft	Non-routine

**Table 2.2. Knowledge-Based Technology Classes (Adapted from Perrow, 1967)**

Perrow (1967) defined the classes as follows: *routine* technologies have few exceptions, are well-defined and analyzable (e.g., mass production); *non-routine* technologies have many exceptions and difficult to analyze problems (e.g., aerospace operations); *engineering* technologies have many exceptions, but they can be handled using well-defined, logical processes; *craft* technologies involve routine tasks, but problems rely heavily on experience, judgment and intuition for decision.

#### 2.3.1.2. *Personnel Subsystem*

Hendrick (1986) considered two major aspects of the personnel subsystem critical to organizational design: (1) the degree of professionalism or the skills and training requirements of the organization in its constituent sub-units, and (2) the psycho-social characteristics of the workforce.

The degree of professionalism relates to whether the employee has limited job discretion (e.g., unskilled or semi-skilled positions) or, at the other extreme, the employee has learned values, norms, and expected behavior patterns prior to entering the workforce (e.g., professional positions). There is a trade-off between formalizing the organizational design or professionalizing the jobs that must be considered.

According to Hendrick (1986), the most useful integrating model of psycho-social influences on organizational design is that of cognitive complexity. Cognitive complexity relates to the range of thinking from concreteness to abstractness. Concrete thinking has been characterized by a high need for structure and order, stability and consistency, closedness of beliefs, authoritarianism, absolutism, paternalism, and ethnocentrism. At the other extreme, abstract thinking has been characterized by a low need for structure and order, openness of beliefs, relativistic thinking, a high degree of empathy and a strong people orientation.

Hendrick (1986) found evidence that: concrete workgroups and managers function best under high centralization, vertical differentiation, and formalization, and abstract workgroups and managers function best with low centralization, low vertical differentiation and little formalization.

#### 2.3.1.3. *Environmental Subsystem*

According to Hendrick (1986), the survival of an organization depends on its ability to adapt to its external environment. Organizations require monitoring and feedback mechanisms to follow and sense changes in their relevant task environments, and the capacity to make responsive adjustments. Task environments, according to Hendrick (1986) vary along two dimensions: *change* which is whether the task environment is stable or dynamic over time, and *complexity* which is whether the components of an organization's environment are few or many in number.

#### 2.3.1.4. *Organizational Design Subsystem*

Hendrick (1986) stated that the structure of an organization can be thought of as having three major components: (1) complexity, (2) formalization, and (3) centralization.

Complexity relates to the degree of differentiation and integration that exists within an organization. According to Hendrick (1986), organizations can be: horizontally differentiated which is the degree of departmentalization and job specialization designed into an organization, vertical differentiation which is the depth of an organization's hierarchy, and spatial dispersion which is the degree to which the organization's facilities and personnel are dispersed geographically.

Formalization can be defined as the degree to which jobs are standardized. In highly formalized organizations, jobs are designed so employees have little discretion over what is to be done, what sequence tasks will be performed in, and how they will be accomplished. In low formalized organizations, employees have more freedom to exercise discretion, and one's mental capacities are depended on more than in highly formalized organizations.

Centralization relates to the degree that decision-making is concentrated in an individual, unit or level, usually high in an organization, providing employees low in the organization minimal input into decisions affecting their jobs. Neither centralization nor decentralization is more preferable than the other but is dependent on the type of decisions required and the environment.

### 2.3.2. Macroergonomics Literature Review

#### *2.3.2.1. Engineering Design*

One of the key macroergonomic issues in engineering design is how to effectively consider ergonomics issues early in the design process. There is a great need for the product design process to include the ergonomics considerations of everyone who may interact with the product throughout its entire life (Dockery, 1994). Two approaches can be taken to resolve this issue: (1) train designers to have the same degree of technical proficiency as the functional experts, or (2) add the experts to the design team in a concurrent engineering process. Considering organizational design issues early also creates engineering design requirements.

Three divisions of United Technologies experimented with approaches to provide more emphasis on ergonomics during design. Pratt and Whitney employed representatives from its customer service and repair centers on design teams during conceptual design. As a result, the number of components were reduced by approximately 50%, the repair time was reduced, and repair became less physically stressful to perform.

At Carrier Transicold, process design engineers were trained in ergonomics principles prior to redesigning the manufacturing facility. As a result, a number of ergonomic considerations were included in the redesign.

At Hamilton Standard, members of the design team were trained in ergonomic principles. In addition, representatives from manufacturing, shipping, and the customer were on design teams. As a result, the build time was reduced by 60%.

Some form of concurrent engineering is crucial for ergonomics product design for two reasons (Dockery, 1994). First, few designers have sufficient depth of knowledge in all aspects of manufacturing and subsequent product life stages to balance those concerns without input from others. Secondly, design teams made up of representatives from all stages of the product's life are more likely to include ergonomics constraints, if only to make their jobs easier.

#### *2.3.2.2. Group Size*

Holloman and Hendrick (1971) conducted a study of the problem-solving ability of different sized groups. With respect to variables such as cohesiveness, member satisfaction, participation, leadership behavior, and productivity, they believed there appeared to be an optimum size beyond which measures of the dependent variable do not increase in direct proportion to the number of members added to the group.

Their study was designed to investigate the question "Do larger or smaller groups make better decisions?" Performance was measured as the ability of the groups to arrive at a single solution to a nonfactual problem under the following conditions: (1) groups are homogeneous

with respect to ability, (2) groups have a prior history of interaction, (3) time limits are uniform, and (4) all groups employ the consensual decision-making process.

Groups were comprised of junior and senior cadets at the Air Force Academy with three, six, nine, twelve, and fifteen members. Members of the group solved the problem individually, and then as a group.

The following conclusions were obtained through this research: (1) within groups of all sizes, group interaction resulted in decisions which were superior to the averaged individual decisions of the group, (2) groups of three were the least accurate of all other groups tested, probably due to the lack of information and ideas available to them, and (3) groups of size six produced the more accurate decisions. Holloman and Hendrick (1971) suggest that the optimum size of problem-solving groups when the criterion of performance is a single best solution should be decided in terms of both the quality of decisions and economy.

### 2.3.2.3. *Computer Support*

Olson's (1989) research focused on short-term, goal-driven collaborations that characterize task forces or ad hoc work groups in the domain of software design. Olson observed the need to provide support to groups to keep track of six streams of information, thereby preventing information overload. The first stream was to keep track of the progress on various assignments and tasks of individuals in the group. The second was to keep track of the current agenda, opening and closing various issues in the current interaction. Information for monitoring and controlling the flow of "turns" should also be provided. The fourth stream consisted of creating, editing, storing and retrieving the work object (e.g., the design, the policy statement, the draft document). Another information stream related to providing information on the various activities designed to help people in various stages of problem solving. These include, for example, brainstorming, group evaluation techniques, and structuring methods for random ideas. Lastly, information relating to recording the reasons for the decisions made or the solutions not taken must be tracked.

The Collaboration Technology Project was a joint venture among Andersen Consulting, the University of Michigan and Steelcase, Inc. (Mack, 1989). The purpose of this project was to provide computer support for project teams of designers, particularly software designers, especially in the early stages of a design process. The conclusions of this research have not yet appeared in the literature.

The environment that computer-supported cooperative work (CSCW) takes place in can play an instrumental role in its success (Cornell, 1989). A number of labs have been developed to assess the ergonomic and environmental aspects of CSCW. Major labs have been developed by Xerox, the University of Arizona, General Motors (EDS), and ICL. According to Cornell (1989), alternate displays, input devices, and user interfaces will need to be developed to make CSCW more desirable to the workforce at large. It is not known what impact facilities have upon groups, the work process, group viability or effectiveness (Cornell et. al., 1989).

The extent to which users (i.e., groups) participate in the design of CSCW systems will impact their success (McNeese, 1992). CSCW presents special design challenges since groups involve the interactions of many participants which can vary with respect to physical location, knowledge, social-organizational culture, and ability. Research was conducted by McNeese



(1992) to develop processes to permit the capture of user involvement in system design using concept mapping and design storyboarding techniques.

Nopachai and Casali (1994) conducted a study on the impact of group decision support systems on group consensus process and outcomes. Eight person groups were given the “Wrecked on the Moon” exercise with three levels of technical support: baseline, manual, and computer-supported. The results showed that there was no significant differences in consensus between levels of technology. Perceived consensus was higher in the computer-supported condition. No significant differences in technical support level were found with respect to decision quality, perceived decision quality, and perceived opportunity to express views.

Cornell et. al.1, (1989) summarized the macroergonomics literature on CSCW by stating that there have been few rigorous studies evaluating the merits of CSCW. However, frequently reported findings are that groups using CSCW appear to reach consensus more quickly, are able to handle larger amounts of information more accurately, and are generally satisfied with the results.

### 2.3.3. Function Allocation

In a macroergonomically designed system, tasks have been properly assigned to humans and machines. The apportionment of tasks to humans and machines in the design of systems is called function allocation (Price, 1985). According to Price, a systematic approach for allocating functions has been an elusive goal of human factors specialists for more than 30 years. The early attempts at function allocation were developed by Paul M. Fitts. He attempted to characterize qualitatively those functions performed better by machines than by humans, and those performed better by humans than machines. The so-called Fitts list had little impact on engineering design practice because the criteria were overly general, non-quantitative, and incompatible with engineering concepts, and because they assumed that functions would be performed by humans or machines alone.

Many systems have been designed with a premature orientation toward some technological solution (Price, 1985). Allocation-of-function decisions, if not made correctly, can be very expensive to correct, especially after hardware design and/or production has begun. The appropriate approach to system design requires that human factors engineers be represented early on design teams. Price (1985) proposed that two teams be used in design. An engineering team describes the engineering concept and a human factors team describes the role of humans. The trade-offs considered by the two teams would result in an overall optimum system design. This balancing of personnel and technological considerations is at the heart of macroergonomics.

## **2.4. The Technological Subsystem Part 1 - The Engineering Process**

Engineering design is important. Poor design can result in higher cost and loss of life. Design is the optimization of a large number of different variables. If the design process can be improved, products will be more competitive in the international market. When major corporations lose business to other companies, it may be because they have not correctly designed their organizations or processes correctly (Suh, 1990). According to Edwin Layton (1976, p. 696):

*“From the point of view of modern science, design is nothing, but from the point of view of engineering, design is everything. It represents the purposive adaptation of means to reach a preconceived end, the very essence of engineering.”*

According to Ferguson (1992), to design is to invent. Engineering design is surprisingly open-ended. Ferguson states that a goal may be reached by many, many different paths, some of which are better than others but none of which is in all respects the one best way. He suggests that anyone who pays attention to the way the human created world has been put together has probably wondered why a particular design was adopted rather than a reasonably obvious alternative.

Utterback (1994) proposed the concept of a “dominant design.” A dominant design is one that wins the allegiance of the marketplace and, hence, competitors and innovators must adhere to it if they hope to command significant market following. The IBM Personal Computer is an example of a dominant design.

Dominant designs arise from new innovations that have gone through intensive churning as the result of products from various manufacturers. When a dominant design finally emerges, competitors stop developing fundamentally different alternatives and focus on process improvement. Dominant designs control the market until a breakthrough in technology starts the cycle over again. Utterback’s concept of dominant designs responds to Ferguson’s query about why the built work looks the way it does.

According to Simon (1969), “Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.” Constraints are the essence of the design process (Meikle, 1989). Designers must integrate a complex set of sometimes contradictory solutions when designing even the most ordinary and apparently predictable object. Mechanical components must be organized to fulfill their purposes efficiently - that is, with as little waste of energy or human effort as possible. Meikle (p. 18) describes the designer’s challenge as follows:

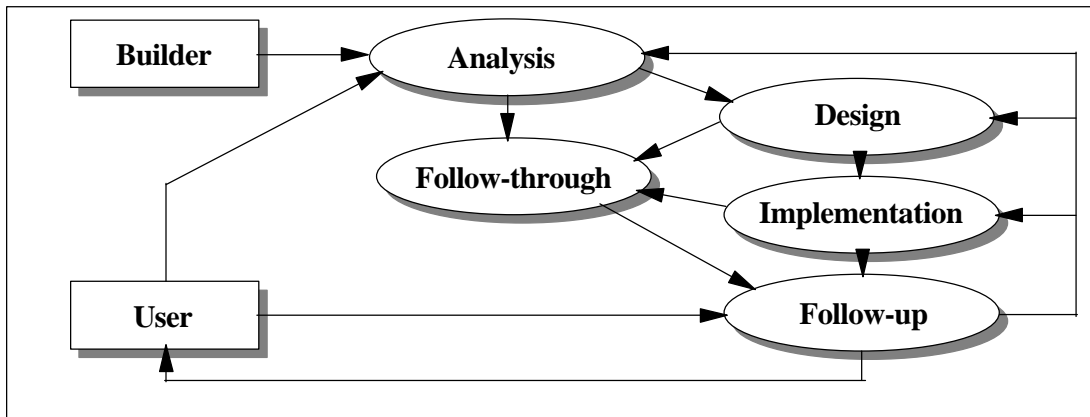
*“The product must be manufactured of durable materials and arranged to require relatively little maintenance and to permit easy repair. Taken as a whole, the assemblage of parts of a product must smoothly fit human bodies and minds - not in the abstract, but in all their multifarious diversity. A product in all of its applications must conform almost organically to the human form, be easy to operate and control, and remain safe during any conceivable use or misuse.”*

More than competitive need now drives the emergence of the 1990’s as a “design decade” that parallels and eventually could rival the 1930’s (Meikle, 1989). The designers of the 1930’s gave emotional expression to the material products of this culture, those of the 1990’s must transcend that goal and literally create the culture of the information age.

The engineering process is a cyclic, recursive process based on the scientific method allowing for learning and continuous improvement (Kurstedt, 1993). According to Kurstedt (1993), design is central to the engineer’s activities and what engineers do.

Design is a component of the overall engineering process as shown in Figure 2.3. The design process encompasses the following activities, all of which must be completed according to Kurstedt (1993): identification, definition, search, establishment of criteria, consideration of alternatives, analysis, decision, specification, and communication.

Kurstedt emphasized that this is not a serial process. As the process proceeds, new information may be developed that requires that the designer backtrack and repeat previously executed steps.



**Figure 2.3. Kurstedt's (1993) Engineering Process**

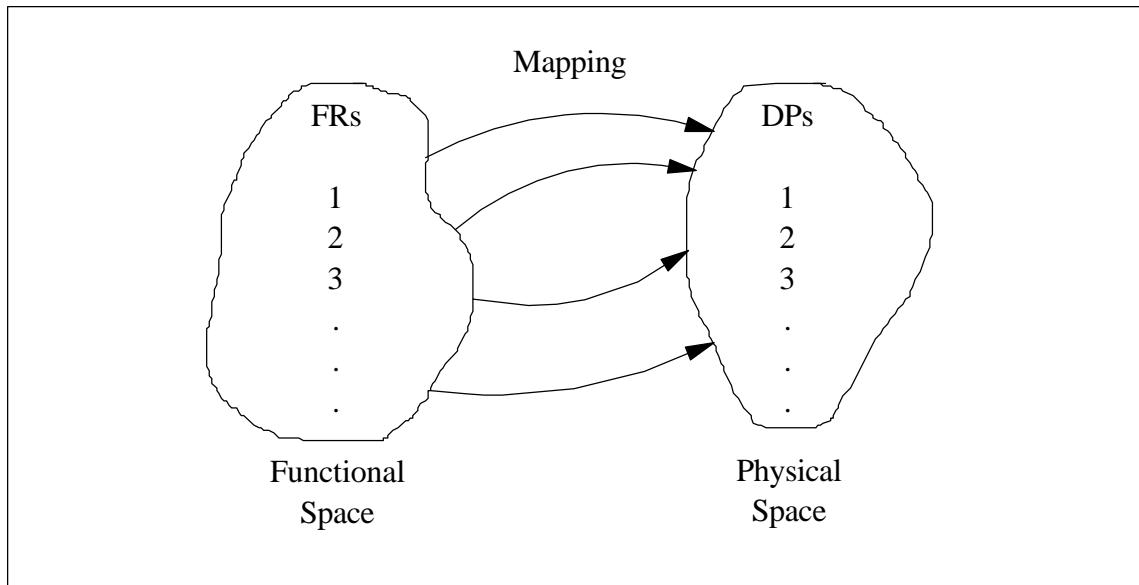
#### 2.4.1. Engineering Decision-Making

Engineering designers are continually making decisions (Siddall, 1972). Many decisions are intuitive, some qualitatively logical, and some based on the laws of science according to Siddall (1972).

Siddall (1972) classified decision-making according to whether it occurs under conditions of (1) certainty, (2) risk, or (3) uncertainty. Decision-making under certainty occurs if each action leads without doubt or risk to a specific outcome. Decision-making under risk occurs if each action has several possible outcomes for which the probabilities are known. Decision-making under uncertainty occurs if each action has several possible outcomes for which the probabilities are unknown.

Designers must use predictions, intuition, and optimization tools in order to develop optimum designs. According to Siddall, the concept of value is central to decision-making in design. Value is the measure of what is good or desirable about a design. Engineering design theory provides tools for designers to make decisions that yield high-value, optimum designs.

Design involves a continuous tradeoff between what we want to achieve and how we want to achieve it (Suh, 1990). The objective of design is always stated in the functional domain (e.g., go to the moon). The solution is always generated in the physical domain (e.g., develop a rocket). Design is the mapping of requirements from the functional space, called functional requirements (FRs), to design parameters (DPs) in the physical space. This relationship is depicted in Figure 2.4. (Suh, 1990).



**Figure 2.4. Design as a Mapping of FRs to DPs (Adapted from Suh, 1990)**

Suh defined design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs in the functional domain and the DPs of the physical domain, through the proper selection of DPs that satisfy FRs (Suh, 1990).

Endeavors ranging from fine arts to engineering are performed subjectively in the realm of creativity. As such, we can appreciate the outcome but do not understand the process that produces the outcome, and can not quantify the results (Suh, 1990). Suh (1990, p. 19) stated that this has been the case in all fields of engineering design:

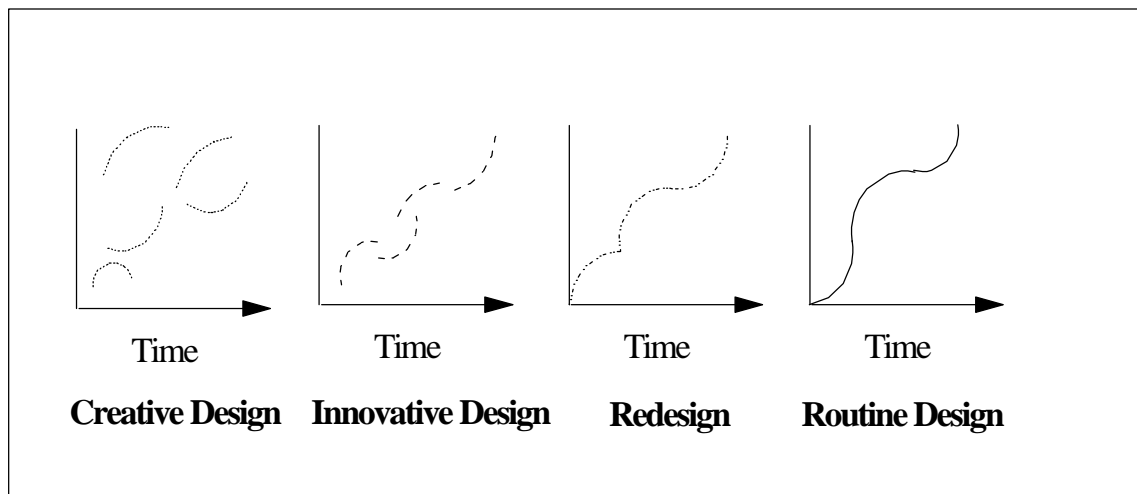
*“The first step toward developing a solution is the synthesis of the overall solution, which involves conceptualization and design of an overall solution by integrating empirical knowledge and scientific principles. This step is then followed by the optimization process, which involves the dissection of the design into components, and the analysis of each component using scientific principles and mathematical tools. That is, engineering consists of analysis and synthesis, science-driven and technology-driven fields, natural and artificial laws, scientific and technological factors, as well as human and societal issues.”*

Sriram et. al. (1989) classified the design process into four categories that are process dependent and product independent. The categories are creative design, innovative design, redesign, and routine design. Creative design occurs when a priori plan for the solution does not exist. The design problem is an abstract decomposition into a set of levels that represent choices

for the components of the problem. The key issue is the transformation from the subconscious to the conscious.

Innovative design occurs when the decomposition of the problem is known, but the alternatives for each of its subparts do not exist and must be synthesized. This design might be an original or unique combination of existing components. There is creative design in this process.

Redesign occurs when an existing design is modified to meet required changes in the original functional requirements. Routine design occurs when a priori plan of the solution exists. The subparts and alternatives are known, perhaps as the result of either a creative or innovative design process. Routine design finds appropriate alternatives for each subpart that satisfies the given constraints. These different design processes are depicted in Figure 2.5.



**Figure 2.5. Categories of Design (Adapted from Sriram, 1989)**

According to Sriram (1989), at the creative end of the spectrum, the design process might be fuzzy, spontaneous, chaotic, and imaginative. At the other, design is precise, crisp, predetermined, systematic, and mathematical.

According to Ball, et. al. (1994), a common view of design tasks - expressed by both psychologists and practitioners alike - is that they are “problems”. In psychological terms, a person has a problem when it is necessary for them to reach some goal which they are not immediately able to achieve. Design tasks fit this definition. They characteristically embody an initially inaccessible goal state (i.e., the desired design) consisting of a number of requirements as provided in a specification.

Bhasker and Simon claimed that problem-solving is such a general process that the results of laboratory experiments on artificial and well-defined problems can be applied effectively to problem-solving in real-world domains (Ball, 1994). However, many design problems are highly ill-defined. Ill-defined means that while some general objectives and constraints are apparent at the outset, considerable amount of time and effort is required to define and structure the problem.

Previous research on design activities identified two fundamental characteristics of design activity. The first, opportunism, represents structure-divergent behavior. The second, structured

behavior, represents the classical top-down approach (Ball, 1994). The literature is mixed on the degree to which designers solve problems opportunistically or in a structured manner.

Ball conducted a longitudinal study of electronic design engineers using a think-aloud process that allowed researchers to track the thought processes of the designers. His study found little opportunistic design behavior. The majority of the behavior fell into the following sequence: (1) a large amount of early design work was spent by designers in developing a clearer understanding of the overriding ill-defined design problem - with particular emphasis being placed on understanding functional requirements and other constraints, (2) a high-level design solution to the overriding design problem was externalized as a set of independent but connected functional modules, (3) a problem reduction (or subgoaling) strategy was then applied - leading to the division of the initial abstract design solution into a collection of relatively distinct subproblems relating to functional modules of the desired artifact, (4) these subproblems were focused on in an essentially sequential manner and solutions were developed depth-first to completion through levels of design detail, and (5) further problem definition and subproblem generation arose if solution models were themselves multi-faceted and at high- or intermediate-levels of design abstraction.

An interesting finding of the Ball study in the context of this research was that Ball suggested that a key function of the design process is to ensure that an effective mapping can be made between a designer's mental model of social considerations (e.g., concerning supervisor requirements and usability issues) and a designer's mental model of the developing technical design solution itself. Ball suggested that the general issue of socio-technical mapping in the design context represents a fruitful area for further empirical research.

Design performance may be described in a number of ways, however, a common set of interrelated, practical measurements remains elusive (Clipson, 1984). Clipson cited a number of factors of successful designs.

Designs should fit their purpose or stated need, and the parts arranged so that there is a "goodness of fit" between the user, and the function, the product, and the environment. The result of a mismatch between the components of a product or between the product and the user, is usually inefficiency of use, significant user adaptation to make the thing work, modifications to the product, and in some cases, product failure or accidents in use.

There must be an economy of production and product cost. Complex functional relationships exist between research and development, production, marketing, and the price of a product. Systems must also be efficient and durable. Problems occur when products do not meet expected levels of efficiency and durability.

All outcomes of designing are imbued with symbolic content. After functional, economic, and engineering considerations have been defined, the emotive issue of "design quality" still has to be considered. Good and bad design is an endless designer debate, and one which is the most difficult to relate to other areas of business performance.

If design is a key to the international competitiveness of corporations and, hence, their continued survival, then designing an effective, efficient, highly productive design process is a priority. Even though design has been characterized as a creative process, there are technological and personnel considerations that can impact on its success. The following sections consider theory that is applicable to two engineering design methodologies.

#### 2.4.2. Sequential Engineering

It is very logical to consider the design of a product prior to designing the processes for manufacturing or supporting the product. Therefore, for much of the period from the Industrial Revolution until the 1980's, the most commonly practiced method was to develop the product and process in a predominantly sequential fashion (Salomone, 1995). Over the years it has become commonplace for the design function to be isolated from the manufacturing and the support organization. Product designs got "thrown over" a metaphorical "wall" by designers to manufacturing and support engineers for their analysis.

The sequential process was an outgrowth of a philosophy that the control of information flow was the key component to product development success (Prasad, 1995b). Power was given to functional organizations to control the flow of information. Sequential engineering appeared to be the right thing to do in this "era of control", according to Prasad (1995).

Tasks during this period were sequentially ordered as requirements definition, product definition, process definition, and delivery and support. Upstream tasks were completed before downstream tasks were initiated. Prasad (1995, p. 250) provides the following detailed description of a typical product development process:

*"In most sequential engineering processes, it was customary for the market research department to determine customer or user needs and throw its sales projection data over the wall to planning. The planning department developed the technical requirements for the product and threw its specifications over the wall to the product engineering group. This group then designed and developed the product on their own, in near-complete isolation from the production process. Later, the prototype was handed over to manufacturing so that their engineers could arrange to manufacture the product on a large scale. Seldom when a product develops this way will it go to production in one shot. Several engineering change orders are issued to fix problems, but due to time pressure, attention can only be given to fix the major show-stoppers (problems)."*

Design practices in the postwar United States evolved in such a way that highly bureaucratic, functional structures inhibited the degree of coordination required by the natural interdependence of parts within complex systems. These structures often evolved into many functional "silos" or multi-layered control structures (Prasad, 1995). Companies used a sequential model in which product designers did their best to meet objectives, then let manufacturing react. This worked well as long as coordination among components was low, there was little interaction between product design characteristics and manufacturing process characteristics, or the product was mature as a result of years of production and redesign (Liker, Sobek, Ward and Cristiano, 1996).

When it didn't work, the major types of problems were: unsuitable product designs for production; unavailability of adequate manufacturing equipment; tight tolerances which could lead to extra work and high scrap generation; problems with parts assembly; and an inability to utilize the existing production equipment, tooling, or automatic assembly equipment (Prasad, 1995). Errors, changes, and corrections took a long time to resolve, often requiring that the process cycle back to the start and proceed sequentially again.

The production and life-cycle cost of a product are determined very early in the overall design process. Many studies suggest that 70% to 80% of the cost of a product is determined very early in the design process. The sequential nature of the process often leads to excessive complexity in designs and higher cost (Venkatachalam, Mellichamp and Miller, 1993). Forcing manufacturing to delay its operations until a product is designed prolongs the product development time, often resulting in missed market opportunities.

Prasad (1995) stated that the result of sequential engineering has been long design and build lead times, unnecessary complexities, a high number of late-in-cycle engineering changes, design with excessive number of parts, retrofits, high customer complaints, manufacturing confusion, blaming mentalities, high scrap and rework, increased field support and service, and only marginal customer appreciation or satisfaction compared to a competitor's product.

Product development today is frequently carried out with the aids of computer tools such as CAD (Computer-aided Design), CAM (Computer-aided Manufacturing), CAPP (Computer-aided Process Planning), etc. These tools, while automating the discrete manual process of product design, have not affected the inherently sequential nature of the process (Prasad, 1995). Time has been saved in a particular phase, however, they have not affected the manual or serial process of passing enriched information between the phases. Significant time is lost in maintaining a serial nature of the process and performing the manual control of the phase interfaces or intraphase data integration.

In summary, the sequential engineering approach to product design, development, manufacturing, and marketing has shortcomings. The product development cycle time is longer because of the basic premise that a new task cannot start until a previous task is completed and signed off. A significant portion, some say 50% to 80% (Prasad, 1995) of manufacturing cost may be committed before manufacturing engineers have a say in the product design. Due to the time lost in development, the final product may not remain suitable or viable for the market that was initially targeted at product launch. This environment fostered the development of another approach to design called *concurrent engineering*.

#### 2.4.3. Concurrent Engineering (CE)

The basic concept of CE is to take the product design process out of the isolated world of design engineers and incorporate the other functional requirements that have, or should have, influence over the design (Farrington and Martin, 1995). CE is not a tool nor a technique but a philosophy. According to a U. S. Army Command Report (1991), this philosophy implies an integrated and continued participation of multifunctional teams in the design of the product, processes, support systems, and disposal procedures. It also implies the integration of multiple engineering and management functions providing for efficient iteration and closure of product and process designs. CE also entails objective choice of options to resolve conflicting requirements based on quantitative or qualitative comparison of trade-offs. CE is an enabling aspect of agile manufacturing (Kleiner, 1997). CE requires an optimization of product and process design. And finally, CE continuously incorporates the requirements and expectations of the user/customer.

The most commonly referred to definition of concurrent engineering is that of Winner as stated in Chapter 1 (p. 4). Given that CE is a force of change, Prasad has chosen to divide the forces that influence the domain of CE into seven agents --- the 7 Ts: talents, tasks, teams,



techniques, technology, time, and tools (Prasad, 1995a). However, according to Evans (1993), teams are the backbone of CE, providing a mechanism for all other CE tools to play their part.

CE attempts to create successful new products by bringing together as early as possible in the design cycle a company's resources and its experience in design, development, marketing, manufacturing, service, and sales (Shina, 1991). These resources are then focused on developing and manufacturing a high-quality, lowest-cost product that meets the customer's needs. CE's significance lies in its challenge to traditional sequential new product development processes, functionally-based organization structures and reward systems, and central decision-making by management.

Schrage (1993) has identified ten characteristics of successful implementations of concurrent engineering. Each characteristic and what is required for that characteristic to be successful is shown in Table 2.3.

Number	Characteristics	What is Required
1	A top-down design approach based on a comprehensive systems engineering process	<ul style="list-style-type: none"> <li>• Top management support that is authoritative, but also participative to allow consensus building.</li> <li>• Development of a systems engineering management plan.</li> <li>• A computer integrated information environment to allow automated configuration management and control.</li> </ul>
2	Strong interface with the customer	<ul style="list-style-type: none"> <li>• Methods for translation of the voice of the customer into key product and process characteristics.</li> <li>• Continuous feedback to the customer as the process evolves.</li> </ul>
3	Multifunctional and multidisciplinary teams	<ul style="list-style-type: none"> <li>• Team members from across the life cycle product and process disciplines - design, manufacturing, and support.</li> <li>• Management and peer acceptance of inputs from all team members.</li> <li>• Equal or near-equal analysis capability by all team members.</li> </ul>
4	Continuity of the teams	<ul style="list-style-type: none"> <li>• Teams must be formed early in the design phase.</li> <li>• Key team members should transition with the product.</li> <li>• Training, organizational acceptance, and incentives for team members who transition.</li> </ul>
5	Practical engineering optimization of product and process characteristics	<ul style="list-style-type: none"> <li>• Methods for incorporating qualitative and quantitative optimization procedures.</li> <li>• Selection of optimization values for key product and process characteristics based on parametric sensitivity analysis.</li> </ul>
6	Design benchmarking and soft prototyping through creation of a	<ul style="list-style-type: none"> <li>• Design by feature methods.</li> </ul>

	digital product model	<ul style="list-style-type: none"> <li>• Product definition and data exchange standards.</li> </ul>
7	Simulation of product performance and manufacturing and support processes	<ul style="list-style-type: none"> <li>• Varying levels of simulation fidelity to support product evaluation through the process.</li> </ul>
8	Experiments to confirm/change high risk predictions found through simulation	<ul style="list-style-type: none"> <li>• Design of experiment methods for variability reduction of high risk product and process characteristics.</li> <li>• Validation and verification of critical components, parts, and technologies.</li> </ul>
9	Early involvement of subcontractors and vendors	<ul style="list-style-type: none"> <li>• Organizational decomposition to identify critical paths, schedules, and required concurrency.</li> <li>• Top management and peer acceptance of early subcontractor/vendor participation.</li> </ul>
10	Corporate focus on continuous improvement and lessons learned	<ul style="list-style-type: none"> <li>• Methods for design tracking and feedback of lessons learned.</li> <li>• Shared computer knowledge bases with open access for key team members.</li> </ul>

**Table 2.3. Schrage's (1993) Ten Characteristics**

*2.4.3.1. Case Studies*

CE has been practiced long enough for there to be a number of successful implementations. The following are but a few of many examples of successes that companies attribute to CE:

*Boeing Commercial Airplane Group:* Boeing is using CE to develop the 777 transport and expects to release design drawings a year and a half earlier than happened with the 767 (Rosenblatt and Watson, 1991).

*John Deere & Company:* Deere used CE to cut 30 percent off the cost of developing new construction equipment and 60 percent off development time (Rosenblatt and Watson, 1991).

*AT&T Company:* AT&T used CE and halved the time needed to make a 5ESS electronic switching system (Rosenblatt and Watson, 1991). As a result of using CE for VLSI (very large scale integration) circuits, part counts were down to one ninth of their previous levels and quality improvements of one hundred times (in surface defects) were created (Syau, 1994).

*Japanese Auto Makers:* The Japanese in the mid- to late- 1980's took roughly half the time U.S. companies did to develop and produce a new automobile. This allowed them to make fewer cars of a given model and keep it on the market for a shorter time. This permitted them to produce a greater variety of products and target them toward more segments of the market, leading to higher sales and profits according to Shina (1991).

*Mercury Computers Systems Inc.:* Using CE, Mercury was able to shorten the cycle for shipping a new board from design approval to a customer for testing to 90 days from the normal 125 days (Shina, 1991).

*Hewlett-Packard:* HP developed the 54600 oscilloscope from idea to finished product in one-third the time that it would have without CE (Wheeler, 1991).

*Cisco Systems:* Cisco designed a dual-bus internetwork router for a high-speed fiber distributed data interface (FDDI) using CE. The board test time was 40 minutes while it would have been at least 60 minutes without CE. The test time is now 20 minutes. Cisco also designed an integrated gateway server using CE and reduced the number of fasteners by 70% (Burnett, 1991).

*ITEK Optical Systems:* After one and one-half years Itek only had four teams considering general business problems. However, once the company realized what the teams were accomplishing, that number was ramped up rapidly to 23, representing a third of Itek's 500 employees (Rosenblatt, 1991).

*Rover:* Rover was able to launch Land Rover Discovery in 18 months as compared with 48 to 63 months for similar products in Europe. As a result it became the best selling product in its class (Syan, 1994).

*GM LT-5 Engine:* Implementation of concurrent engineering created a simpler organizational design which allowed the engine for the Lotus Corvette to be made in four years rather than the usual seven. Team members set their own deadlines and agreed on what constituted quality and performance. CE helped identify problems early in the project, rather than after time and money budgeted for the project were spent (Snoderly, 1992).

*Chrysler Viper:* The project to develop a car that was the resurrection of the AC Cobra started in 1989 and was in limited production in record time, just 3 years. This project was performed by teams consisting of management, engineering and union workers. This car was developed with a budget much lower than previous work by Chrysler, Ford, or General Motors (Snoderly, 1992).

#### 2.4.3.2. *CE Tools and Techniques*

In CE, the key ingredient is teamwork, however, there are a number of tools and techniques that play a big role according to Rosenblatt (1991). There are not a set of tools and techniques that are unique to CE. However, the following should be part of the concurrent engineer's lexicon (Hall, 1991).

*Quality Function Deployment (QFD):* QFD is an important tool to facilitate multi-functional planning and communication in a CE environment by providing a structured framework to translate the "voice of the customer" into the actions and resource commitments needed to

meet customer expectations (Menon, O'Grady, Gu and Young, 1994). QFD is a matrix technique that documents customer requirements and is used to help prioritize design criteria (Peck, 1995) Menon, et. al. (1994) state that user experiences confirm that QFD can: (1) reduce product development cycle time, (2) improve customer satisfaction, and (3) increase competitiveness. By using QFD, a product development team determines what customer attributes are important (because either the customer wants them or the competition has them) and the set of engineering characteristics to be addressed to improve each customer attribute (Hall, 1991).

*Design for Manufacture and Assembly (DFMA):* DFMA is a design philosophy that alerts design engineers to the manufacturing implications of their work (Hall, 1991). A large number of methods and non-standard terminology and computer systems have been developed to implement DFMA (Syam and Swift, 1994). Consideration of manufacturing problems at the design stage is a major way of reducing manufacturing costs and increasing productivity. DFMA focuses on production cost so that part complexity can be traded off against number of parts and the difficulty of assembling them (Hall, 1991).

*Robust Design:* Robust Design is a method of design which establishes a specific approach to design. The objective is to minimize the deviation from the desired target level (for example, voltage), which minimizing manufacturing costs (Salomone, 1995). According to Salomone (1995), these deviations are typically due to three areas: manufacturing process, environment, and material variations. Robust design is not the same as rugged or conservative design. Robust design seeks to reduce product sensitivity to the sources of variability through careful selection of design values (Hall, 1991).

*Quality Loss Function:* The premise of variability reduction is that any deviation from a product characteristic's optimum value, even though within tolerance, is costly. The quality loss function is an equation to calculate the cost: it says that the loss of quality increases with the square of the deviation from the target value (Hall, 1991). The cost of quality manifests itself in warranty costs, maintenance costs, and loss of customer satisfaction or good will.

*Ishikawa's Seven Tools:* Kaoru Ishikawa developed seven tools in the 1940's in Japan for which he received Japan's Deming Prize. These tools, not unique to CE, are: (1) cause and effect diagrams (AKA fishbone diagrams), (2) check sheets, (3) histograms, (4) Pareto diagrams, (5) control charts, (6) scatter diagrams, and (7) binomial probability paper.

The above are by no means all of the tools and techniques used in CE implementations. Many methods embody other methods. Any tool or technique, including Total Quality Management, that reduces cycle time, improves quality, or reduces costs could be considered a CE tool or technique.

#### 2.4.3.3. *Current Research*

Design is not an easy subject to research unlike domains like physics, chemistry, or biology where theories and hypotheses can be tested by laboratory or controlled field experiments

(Dixon, 1987). Because of the involvement of people and organizations, design is like cognitive psychology or sociology in terms of research. According to Dixon (1987), design is a process, and processes are not the usual subject of theoretical formulations.

CE is still a relatively new field of research. Prior to 1992 most literature on CE was anecdotal, definitional, or conceptual which was necessary and appropriate at that time, given the state of knowledge about the subject matter (Gerwin and Susman, 1996).

Today, research is focused primarily on: (1) developing a better understanding of why CE is proving to be a successful methodology in a number of market sectors, and (2) developing tools that facilitate CE. For example, Susman and Dean developed a model of CE effectiveness based on an organizing framework that considers integrative mechanisms, group process, codification/computerization, and task conditions (Gerwin and Susman, 1996). Table 2.4 shows a list of the variables that a number of researchers have found, through survey and case study research, to be important.

<b>Integrative Mechanisms</b>	<b>Group Process</b>	<b>Codification / Computerization</b>	<b>Task Conditions</b>
Team boundaries - Suppliers - Customers Fewer projects assigned Collocation Assign downstream personnel upstream Goal setting and formal reviews Performance evaluation Team-based rewards	Ease of decision making Number of influences Two-way communication Overlapping tasks - Preemptive - Iterative - Distributive Release and use of incomplete information Set-based design Activity concurrency	Common language Design heuristics Virtual collocation Interface technology Scope of design rules Speed of access to data Goal programming Computer technology integration	Newness Riskiness Uncertainty Complexity Interdependence Design evolution Design sensitivity Early/late product life cycle

**Table 2.4. An Organizing Framework for CE  
(Adapted from Gerwin and Susman, 1996)**

Gerwin and Susman offered a number of generalizations concerning the current state of the art in CE research (Gerwin and Susman, 1996). They said that an increasing amount of CE research is empirically based, as is this research. Interactions among variables are as important as main effects and that tests of hypotheses involving interactions among variables are needed, which this research considers. They stated that more research is focusing on the decision-making and problem-solving behaviors that occur within teams during CE, which is also considered by this research. CE is moving into the software development domain. Research is investigating the conditions under which using CE is appropriate rather than implicitly assuming it is the best answer under all circumstances. This is a tenet of this research. And finally, they said that researchers are beginning to investigate limitations on the appropriateness of using technical tools and techniques in a CE environment, also considered by this research.

The DARPA (Defense Advanced Research Projects Agency) Initiative in Concurrent Engineering (DICE) mission includes developing, integrating, and disseminating technologies for CE (Reddy, Wood and Cleetus, 1991). According to Reddy (1991), studies and workshops in the late 1980's convinced DARPA that it should borrow the best practices from industry around the world and apply them to weapons systems development, in particular the practice of considering all aspects of a product concurrently, including manufacturing and logistics, for the sake of high quality, low cost, and short time to market.

DICE was not concerned with developing techniques for design and development automation, but, rather, to give people working in large and scattered organizations the same freedom of interaction and information exchanges as is enjoyed by a small team working in the same room. The administration of the DICE program has been performed by the Concurrent Engineering Research Center (CERC) at West Virginia University.

In order to successfully demonstrate CE in an environment of multiple, geographically dispersed disciplines with many teams, covering the life cycle of a product, the DICE Program has demonstrated or developed the following technologies (Reddy, 1991): the transparent collocation of programs (any program in any workstation is available to other workstations as if it were hosted there); computer-based meetings, with text, voice, and graphics available by means of the network; a unified, shared product information base; and shared access to data in many object languages. Also demonstrated are "wrappers" (interface software for integrating engineering tools with the shared database and other services); browsing, via hypermedia, through data on the design intent and rationale; and constraint tools for managing customer requirements and enforcing design rules and process limitations.

Since 1988, the MIT Intelligent Engineering Systems Laboratory has been working on a computer-based architecture program called the Distributed and Integrated Environment for Computer-Aided Engineering or Dice (Sriram, 1993). While this project should not be confused with West Virginia's DICE program, they have similar objectives. The purpose of this project is to facilitate concurrent engineering by addressing coordination and communication problems. Specifically, this research is addressing: frameworks, representation issues, organizational issues, negotiation/constraint management techniques, transaction management issues, design methods, visualization techniques, design rationale records, interfaces between agents, and communication protocols.

Several research groups are jointly developing the Palo Alto Collaborative Testbed (PACT). PACT is a concurrent engineering infrastructure that encompasses multiple sites, subsystems, and disciplines (Cutkosky, 1993). The purpose of PACT is to integrate existing tools into a framework that has three dimensions: (1) cooperative development of interfaces, protocols, and architecture; (2) sharing of knowledge among systems that maintain their own specialized knowledge bases and reasoning mechanisms; and (3) computer-aided support for the negotiation and decision-making that characterize concurrent engineering.

#### 2.4.4. Summary of the Engineering Process

While Simon (1969) has argued that a science of design is possible and that some day we will be able to talk in terms of well-established theories and practices, today engineering design lacks sufficient scientific foundations (Bahrami and Dagli, 1994). We live in a man-made

environment and use the products of human creativity but we cannot fully describe or understand the process that produces the design. Until a scientific foundation for design is developed, design will continue to be guided by empiricism, intuition, and experience.

However, there is a great deal of interest in developing communication, collaboration, and decision-support tools for concurrent engineering. The ideal environment envisioned would enable any team member to spontaneously communicate (and thereby collaborate) with any other member (or group) (Reddy, 1993). Much of the research in concurrent engineering is focused on making this vision a reality through computer support.

## **2.5. The Technological Subsystem Part 2 - Computer Support**

The type of computer support considered by this research is computer-supported cooperative work (CSCW). CSCW is used in this research primarily to support the conceptual design process.

### 2.5.1. Computer-Supported Cooperative Work (CSCW)

Computer-supported cooperative work is a new field of research, drawing together: (1) social and behavioral scientists whose theoretical interests include factors that affect human communication and the performance of groups, with (2) scientists developing systems that are more appropriate to users' needs by developing a more refined understanding of how people work together (Galegher and Kraut, 1990). CSCW is a computer-assisted coordinated activity carried out by a group of collaborating individuals for problem-solving or communication (Baecker, 1993).

Communication is a very important aspect of group success. Computer-supported cooperative work technology potentially improves the interaction of group members. This section presents the results of research on this technology as it pertains to the use of CSCW in an idea generating, decision-making environment for conceptual design.

CSCW draws together the interests of social scientists concerned about the factors that affect human communication and performance and system builders seeking a more refined understanding of how people work together as a basis for design (Galegher and Kraut, 1990). Kraemer and Pinsonneault (1990) further differentiated CSCW into two broad technological support systems for group processes: Group Decision Support Systems (GDSS), and Group Communication Support Systems (GCSS) (Kraemer and Pinsonneault, 1990). Typical GDSS include decision-support tools (e.g., PERT, budget allocation models and choice models) plus group support tools (e.g., automated Delphi technique, nominal group technique, and decision conference). Typical GCSS include interactive video, e-mail, voice messaging, and video conferencing (McGrath and Hollingshead, 1994).

The differentiation of CSCW into GDSS and GCSS was important because studies have shown that the impact of these systems has contradictory impacts on dependent variables like satisfaction. A review of the literature at the CSCW level would show greatly mixed results.

CSCW facilitates team functions by: (1) supporting group decision-making and consensus building, (2) improving communications, (3) promoting greater innovation and creativity, (4) enhancing the ability to focus on the task, (5) increasing the number of ideas generated, and (6) improving team productivity, team building and ownership (Dallavalle, 1992).

The Army conducted a study of CSCW in early 1992 using the GroupSystems software (Gantt and Beise, 1993). Post-test interviews indicated that the less computer literate found CSCW more effective than did their high-powered colleagues. Using a five point Likert scale with five being the most favorable rating, the following results were obtained:

- Willingness to use groupware tools again 4.4
- Task accomplishment 4.3
- Even participation 4.2
- Satisfaction with process 4.1
- Good outcome 3.9
- Commitment to results 3.8

These results demonstrated that groupware was overall favorably rated. Participants initially believed that learning groupware was a barrier. But they felt that it would be beneficial after frequent use. Some participants feared using a computer, but they overcame this trepidation. Other members felt that interaction was limited by the system's structure. However, in general, the results of this research showed that participants reacted favorably to the use of CSCW.

The following subsections present the literature on CSCW in terms of GDSS and GCSS as it relates to the following variables: performance, participation, consensus, member reactions, leadership and satisfaction. Meaningful group support technology research should be clearly tied to both group performance and satisfaction variables, because the purpose of these systems is to promote the overall efficiency and quality of group work (Post, 1992). A final section is provided specifically on the impact of CSCW on group size.

#### 2.5.1.1. *Performance*

Group decision support systems (GDSS) focus the efforts of group members on the task, increase the depth of analysis, increase the task-oriented communication, increase the clarification efforts, increase decision quality, and increase the overall quantity of effort put in the decision process (Kraemer and Pinsonneault, 1990). GDSS can increase or decrease decision time based on the task, the participation level, and the degree of focus of the group according to Kraemer and Pinsonneault.

GCSS increase the decision time and decision quality as a result of increasing the depth of analysis, increasing participation, decreasing the domination by a few members, and decreasing consensus and cooperation (Kraemer and Pinsonneault, 1990).

Boeing conducted a major field study of group support technology in 1991 (Post, 1992). Six hundred and fifty four participants, with an average group size of 10.2, participated in sixty four sessions averaging 4.7 hours each. The participants rated the effectiveness of the technology high in terms of enhanced quality on a five point scale of 3.91, more insightful information - 3.90, and improved channels of communication - 3.82. The highest response was the participants' willingness to participate in another session (4.37). The savings to Boeing from this study were: (1) \$432,260 total labor dollars saved, (2) \$8,754 mean labor dollars saved per session, (3) \$1,446 mean labor dollars saved per session hour, (4) 11,678 total labor hours saved, and (5) 1,773 total days of flowtime saved. The result was an average labor saving of 71% and an



average reduction of elapsed time of 91%. Boeing's return on investment for this pilot project was 170% the first year (Post, 1992).

Bellcore conducted a study of the productivity of using CSCW technology in early 1991 (Dallavalle, 1992). Four quality improvement teams used CSCW technology to work on ways to improve their products, services, and basic business planning processes within the company as well as improving teamwork across diverse work groups. The results of a follow-up survey showed that compared to traditional meetings: (1) 40% felt that CSCW was more than three times as productive, (2) 40% felt that it was three times as productive, and (3) 20% felt that CSCW meetings were twice as productive. Additionally, 40% felt that their task was accomplished in less than 1/3 the amount of time while 60% felt that their task was accomplished in 1/3 the amount of time.

IBM conducted a year-long study of CSCW with 30 groups using the technology to solve problems in production-line quality (Vogel, et. al., 1990). The results were that teams using the technology saved an average of 50% in labor costs over conventional methods. They also reduced the elapsed time from the beginning to the end of their projects by an average of 91%.

Because of this success, a second year-long study was conducted at six other IBM sites with 50 groups. The results were that average labor costs were reduced by 55% and elapsed times for projects of all types were reduced an average of 90% (Grohowski, et. al., 1990).

#### *2.5.1.2. Participation*

GDSS and GCSS increased participation and decreased the domination of the group by one or a few members (Kraemer and Pinsonneault, 1990). One study showed that GDSS had more equal levels of member participation than manual groups (George, Easton, Nunnemaker and Northcraft, 1990). Not all studies supported this finding (Nunamaker, Applegate and Konsynsky, 1987). Kraemer and Pinsonneault suggested that participation may have not been properly controlled for in a number of research projects because group members had a predisposition toward the use of computer technology.

#### *2.5.1.3. Consensus*

According to Nopachai and Casali (1994), the influence of a GDSS on consensus depends on the particular features of the GDSS, the nature of the group's task, the composition of the group, and how the group uses the GDSS. Some of these may positively facilitate the process and outcomes and others may negatively influence it.

Poole, Holmes, and DeSanctis (1988;1991) identified seven effects that impact on consensus. There was a greater expression of affect, both positively and negatively, in CSCW than in face-to-face modes. Given that negative feelings are portrayed more strongly than positive feelings, there can be a decrease on consensus. Secondly, by emphasizing written rather than oral communication, users became more committed to their positions, resulting in a decrease in consensus. Since CSCW de-emphasized personal relations, conflicts may not tend to be taken personally resulting in higher consensus on the outcome. By equalizing user participation, consensus may be either increased or decreased. Consensus may increase if all participants have had a chance to contribute and conflict resolved. Consensus may decrease if there is much unresolved conflict and discussion time is greatly increased. Because CSCW is clearly structured,

users understand their roles and the process, resulting in less conflict and social uncertainty. Hence, consensus can be increased. Voting can increase or decrease consensus. Voting may cause discussion to increase, resolving conflict or it may be a disincentive to reach consensus if the users know that compromise may not be necessary. And finally, CSCW may result in a wider range of alternatives being explored which may increase consensus as a result of finding a solution that meets the needs of all parties.

Other scholars have shown the impact of CSCW on consensus to be mixed. GDSS increased consensus-reaching (Kraemer and Pinsonneault, 1990). This is not inconsistent with greater participation because of the increased focus of the group on the task. However, not all studies agree with this conclusion (George, Nunamaker and Vogel, 1988; Turoff and Hiltz, 1982). GCSS decrease consensus-reaching, especially in groups in the early stages of development (Kraemer and Pinsonneault, 1990).

#### *2.5.1.4. Member Reactions*

Computer-supported groups tend to de-emphasize personal relations and experience less interpersonal attraction (two studies). However, one study found that computer-supported groups developed in a relationally positive direction (Kraemer and Pinsonneault, 1990).

Groupware and collaborative efforts are most successful at the lower levels of an organization (Hsu, 1993). Lower-level employees are more used to workgroup projects, have fewer incentives for competitive behavior, and usually are so disempowered that they prefer to wrap their comments, ideas, and suggestions in anonymity according to Hsu.

#### *2.5.1.5. Leadership*

Hollingshead and McGrath's analysis of studies on CSCW showed that computer groups were less likely to have emergent leadership in studies conducted by Lewis in 1982 and Ziguers, Poole and DeSanctis in 1988, but were more likely to have decentralized leadership (one study), and less stable leadership (one study) (McGrath and Hollingshead, 1994).

#### *2.5.1.6. Satisfaction*

GDSS increased the satisfaction of the group members with the decision and with the decision process (Kraemer and Pinsonneault, 1990; Nunamaker et. al., 1987). Members can rapidly share information and educate each other in a non-threatening fashion which has a positive impact on satisfaction (Nunamaker, Vogel and Konsynski, 1989).

The previously cited Boeing field study showed that there was a high level of satisfaction and utility associated with the results of the technology supported group sessions (Post, 1992). On a six-point scale, participants responded that the sessions added value (5.54).

Connolly et. al. (1990) conducted an experiment to evaluate the effects of anonymity and evaluative tone on idea generation in computer-mediated groups. Evaluative tone was manipulated through a confederate group member who entered supportive or critical comments into the brainstorming system. Identified groups working with a supportive confederate were the most satisfied and had the highest levels of perceived effectiveness, but produced the fewest original solutions and overall comments.

#### 2.5.1.7. *Group Size*

Research has shown that the process and outcome of group meetings is different among groups of different sizes (Dennis, 1990). Group size may be an important determinant of the value of CSCW (Vogel and Nunamaker, 1990). There is evidence to suggest the GDSS technology may be more effective for larger groups (George et. al., 1988). In traditional (i.e., non-computer-supported) groups one member speaks at a time. Group efficiency degrades with increased group size (Nunamaker et. al., 1989). CSCW permits every member to contribute at the same time. Given that the number of conversation opportunities is given by  $n(n-1)/2$  where “n” is group size (Hare, 1976), the value of CSCW increases as a function of group size.

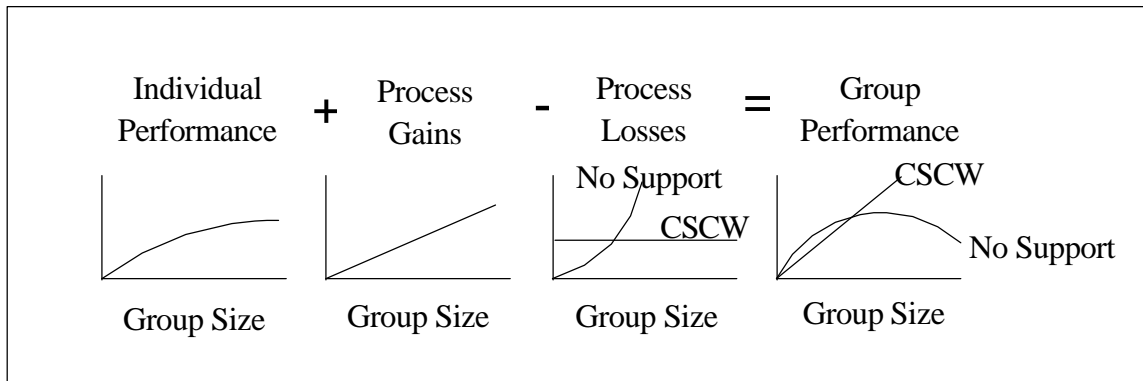
Nunamaker differentiated between the physical and logical size of groups. Logical size refers to the degree of overlap of experience, culture, and knowledge among members. Small multi-cultural groups that have multiple and often conflicting perspectives, points of view, diverse knowledge domains, and opinions may be logically large. Logical size is a more important indicator of group size than its physical size (Nunamaker et. al., 1989).

The optimum group size for groups facilitated by computer support may be quite large (Nunamaker et. al., 1992). While process losses increase rapidly with group size in a manual group (Steiner, 1972), Valacich et. al. (1990) confirmed a model of group performance that proposed process losses to be relatively constant across group size.

Brainstorming is an important component of computer-supported cooperative work. Over 20 studies have been conducted during the last 25 years and none have found that real, interacting groups using the brainstorming technique were more effective than nominal groups (individuals generating ideas alone that are then pooled together) (Gallupe, 1992). Gallupe cited a number of theories why group brainstorming is not more effective including: production blocking (i.e., individuals generate more ideas because they can get ideas out as soon as they are thought), evaluation apprehension theory (i.e., individuals are inhibited because they think others may criticize their ideas), and social loafing which suggests that individuals working in groups have a tendency to “free ride” on the efforts of others.

Seven studies were conducted to compare the effects of electronic brainstorming with traditional and nominal brainstorming (Gallupe, 1992). The results were that electronic brainstorming was more productive and satisfying than either traditional or nominal brainstorming. Electronic brainstorming was not affected by social loafing. And finally, the productivity of electronic brainstorming increased with group size. Larger computer groups generated more ideas per member than did small computer groups in five studies (Kraemer and Pinsonneault, 1990).

Nunamaker et. al. (1990) has summarized the findings of the various studies on group size with Steiner’s concept of process losses to create the model of group performance as a function of group size shown in Figure 2.6.



**Figure 2.6. Performance as a Function of Group Size**  
(Adapted from Nunamaker, et. al., 1990)

## 2.6. The Organizational Design Subsystem - Groups

This section provides a high-level overview of the various theories of groups. The issue of individual versus group performance in engineering design is considered. A section on the various types of teams used in engineering is presented followed by a discussion on the effect of group size on a number of factors including: performance, participation, consensus, member reactions, leadership, and satisfaction.

### 2.6.1. Group Theory

There are a number of theories of groups. The following subsections present overviews of some of those theories.

#### 2.6.1.1. Functional Theory

Functional theory, developed by Parsons (Hare, 1992) describes four basic functions that must be fulfilled for any social system or small group to survive. The four functions are: the members of the group must share a common identity and be committed to the values of the group; they must have or be able to generate the skills and resources necessary to reach the group goal; they must have rules that allow them to coordinate their activity and enough feeling of solidarity to stay together to complete the task, and they must be able to exercise enough control over their membership to coordinate the use of resources and member roles in pursuit of their common goal.

Given fulfillment of the above functions, then the typical group develops through four stages: (1) commitment to basic values and overall purpose of the group, (2) acquisition or development of resources, (3) defining roles and developing morale, (4) carrying out specific group activities, coordinated by leadership.

Functional theory suggests that the culture of the group must first be adequately and accurately assessed prior to development of tools. Secondly, the stage of the group must be determined and the existence of prerequisites for that stage verified.

#### 2.6.1.2. *Dramaturgical Theory*

Dramaturgical theory depicts small group behavior as a play with actors, roles, and an audience (Hare, 1992). Task activities from a dramaturgical perspective parallel those of functional theory: (1) developing an actable idea, (2) staging, (3) recruiting actors and training them for roles, (4) enactment of the play, (5) assessing new meanings for the actors and audience.

Dramaturgical theory is most useful for understanding groups engaged in highly creative tasks. Therefore, this theory provides another point of perspective of analysis of a group.

#### 2.6.1.3. *Exchange Theory*

In exchange theory social interaction is viewed as the exchange of material or nonmaterial goods and services (Hare, 1992). These media of exchange could be money, power, influence, and commitment. The modalities of exchange are seeking, offering, depriving, accepting, ignoring, and rejecting. Exchange theory could be used to assess the interactivity of the group to determine its impact on conflict and consensus.

#### 2.6.1.4. *New Field Theory*

New Field Theory or SYMLOG (System for the Multiple Level Observation of Groups) (Hare, 1992) assumes that there are three basic dimensions of interpersonal behavior: (1) dominance versus submission, (2) positive versus negative, and (3) forward (serious or conforming to the requirements of the task) versus backward (expressive or non-conforming).

SYMLOG provides a tool for assessing the relationships between individuals and how they might be expected to interact with each other. SYMLOG can be used as a diagnostic tool to help identify relationship-based conflict. SYMLOG can be used to change group behavior. Bringing out information about behavior, attitudes, or perceptions through attempts to measure them often tends to change them.

The SYMLOG system can be used in natural groups as well as for use in laboratory and experimental groups. It is especially appropriate for group self-studies. SYMLOG is based upon observations of "behavior". Based on the observed behavior, interventions can be designed to modify that behavior

#### 2.6.1.5. *Time, Interaction, and Performance Theory*

Time, Interaction, and Performance or TIP Theory is an attempt to conceptualize groups and group activity at a level of molarity and complexity. This theory reflects, to some degree, the nature of groups in everyday life (McGrath, 1991). TIP Theory is best explained in terms of 12 propositions. The first proposition is that groups are assumed to be complex, intact social systems that engage in multiple, interdependent functions, on multiple, concurrent projects, while partially nested within, and loosely coupled to, surrounding systems. The second proposition is that all group action involves one or another of four modes of group activity: (1) Mode I: inception and acceptance of a project (goal choice), (2) Mode II: solution of technical issues (means choice), (3) Mode III: resolution of conflict, that is, of political issues (policy choice), and (4) Mode IV: execution of the performance requirements of the project (goal attainment). The third proposition is that the four modes of activity are not a fixed sequence of phases but, rather

are a set of alternative kinds of activity in which the group and its members may engage. The fourth proposition is that behavior in work groups shows many forms of complex temporal patterning, including: (1) temporal aspect of the flow of work in groups, which raise issues of scheduling, synchronization, and time allocation, (2) problems of efficiently matching periods of time with bundles of activities, and (3) entrainment processes leading to pattern of synchronization, both of group members' behavior with one another, and of group behavior with external events. The fifth proposition is that all collective action entails (at least) three generic temporal problems that both organizations and individuals must reckon with. The sixth proposition is that a temporally efficient flow of work in groups requires complex matching of bundles of activities to particular periods of time. The seventh proposition is that one major form of temporal patterning is social entrainment. In TIP theory, proposition number eight is that the group interaction process refers to the flow of work in groups at a micro level. The ninth proposition in TIP theory is that it is assumed that at any point in interaction, a group has a current purpose of objective that can be regarded as its focal task. The tenth proposition is that each act can be regarded as either germane to the group's current "focal task" or not germane to it. The eleventh proposition is that acts have situated, rather than generic, meanings in relation to the modes, functions, and paths of group activity. And finally, various aspects of the flow of work in groups are reflected in different forms of aggregation of acts.

The theory suggests that the pattern of group activity can be altered by changes in membership, changes in the type and difficulty level of the projects and tasks the group is undertaking, and changes in operating conditions under which the group is working.

## 2.6.2. Individuals Versus Groups

### *2.6.2.1. Overview of Theory*

Some of the earliest experiments in social psychology considered the issues of individuals and groups. There is a large body of knowledge on this subject, much of it contradictory. The following attempts to take a high-level view of the body of knowledge and cite those major results that could be applicable to engineering groups. Specifically, the current theory of individuals versus groups was compared on the basis of group makeup, efficiency, productivity, effectiveness, judgment, and the type of problem.

The presence of other persons may change the content of an individual's activity from personal to group-oriented, it may increase his activity if he or she is spurred on by the implied competition, or it may depress his activity through distractions, conformity to norms, or group resistance to the task (Hare, 1976). Group decision-making can be valuable if the group members have learned to work together effectively and shared leadership is practiced (Barker, 1991).

The research literature indicated that groups were superior to individuals in problem-solving because learning is facilitated by interaction (Tuckman and Lorge, 1965). However, a study by Tuckman and Lorge showed that groups of five were more likely to be more effective than individuals, not so much on account of the greater effectiveness of groups in solving problems, but rather on account of the greater probability of getting a good solution from a group than from any one individual.

When groups were compared in the solution of the same types of problems, the groups were generally found to be more efficient than individuals --- especially if the members are friends (Hare, 1976). Olson suggested that groups are not as efficient as individuals due to the time spent in coordination (Olson, Olson, Carter and Storrosten, 1992). In a study of the software design process, approximately 20% of the effort related to coordination.

The superiority of the group over an individual with respect to productivity was usually greater on manual problems than on intellectual tasks (Hare, 1976). Hare further stated that the group will lose its superiority in accuracy and efficiency if: (1) no division of labor is required, (2) problems of control are too great, (3) the group develops a standard of productivity that is lower than that of a separate individual.

In terms of the number of individual hours required for a task, an individual was usually more productive than a group (Hare, 1992; Barker (1991). Individuals were found to be superior when the amount of effort invested, as measured by man-hours required for solution, is considered according to Shaw (1981).

Research data concerning individual versus group performance indicated that effectiveness depends upon the past experience of the persons involved, the kind of task they are attempting to complete, the process that is being investigated, and the measure of effectiveness (Shaw, 1981).

Given a minimal level of trust and good will, a group was capable of producing a greater quantity and variety of ideas than the average individual (Barker, Wahlers, Watson and Kibler, 1991). Groups produced more and better solutions to problems than did individuals, although the differences in overall time required for solution were not consistently better for either individuals or groups according to Shaw (1981).

Shaw (1981) summarized previous research on the judgment of individuals versus groups as follows: (1) group judgments are seldom less accurate than the average individual judgment and are often superior, (2) the type of task may determine whether group judgment will be superior to individual judgments, and (3) a single capable individual may perform as well or better than a group.

Another perspective of group versus individual performance related to the type of problem being solved. The research literature suggested that multi-stage problems require that an individual or group solve one step before proceeding to the next step. Another issue relates to whether the problem is conjunctive or disjunctive. Conjunctive problems exist when success depends on all (or most) members. Disjunctive problems can be solved by a single member of a group.

Smith tested these issues over a ten-year period in a classroom setting (Smith, 1989). His findings were: (1) the advantages of groups were most evident for conjunctive type of tasks, (2) groups did no better than would have been expected of their single best member on disjunctive tasks, and (3) the greater the number of tasks, the more significantly did groups' performance surpass individuals'.

Given the mixed results provided above, it is difficult to know when individuals or groups are more appropriate. Barker (1991) provided a good overview of the issue, stating that groups should be used rather than individuals when: (1) a common understanding and information base will be achieved by participants, (2) a group setting provides an environment that legitimizes a variety of viewpoints, (3) a group is capable of producing a greater quantity and variety of ideas

than the individual, (4) a commitment to action can be born of teamwork, arguing, building of alternatives, and movement toward choice, and (5) the give-and-take of open discussion can tap the group's natural creativity.

The commitment to the group, and beyond it to the organization and beyond that to Japan Inc., is well-known, and by all economic measures is astoundingly productive (Handy, 1996). According to Handy, this commitment requires the discipline of punctuality, the uniformity, and in a way, the tyranny of the group: the peer pressure, the need to conform, the lack of any private space, both physically and psychologically. Some of these stifle individuality. Handy concludes that the best way, as so often, must be to have a bit of both, the middle way: tight groups and free individuals. Individuals who stick their heads above the gang - but do not keep them there are valuable to the organization. Organizations that are committed to a goal - but not a purely selfish one make contributions to the economy and society.

#### 2.6.2.2. *Individuals Versus Groups in Engineering Design*

If teams are the norm in concurrent engineering processes, and individuals are the norm in sequential engineering processes, the literature is very mixed on the relative effectiveness of each. In the *Journal of Engineering Design*, Holt offered the following perspective on the effectiveness of individuals versus teams in design (Holt, 1993, p. 371):

*“Some claim that really good ideas only came from individuals: ‘When the devil wanted that nothing should happen, he organized a group.’ The assumed superiority of the individual, which lies behind this statement, may be somewhat exaggerated. Groups can generate good ideas. The difference may be illustrated by referring to the crossword puzzle --- ‘the design is best done by an individual, the solution by a group.’ ”*

There are two different types of thinking required in the design process: (1) problem-oriented thinking which is usually the domain of engineers and researchers, and (2) solution-oriented thinking which is usually the domain of designers (Frost, 1992). Groups and individuals are responsible for the creation of designs. Hongo pointed out in Andreasen that the creative and intuitively gifted employees, as well as the methodologically gifted ones, need to be cultivated (Andreasen, 1991).

Few designs are truly done by individuals. Designers continuously exchange information with other persons even if not in teams (Ehrlenspiel and Dylla, 1993). The role of designers is a central, integrative one, for they must interact with people in virtually every part of the company, as well as people outside. Often it is not possible to identify an individual as “the designer” and the design must be regarded as a team or company activity (Taylor, 1993).

Tools are under development to improve the effectiveness of both individuals and groups in design. Holt stated that these “computer-aided creativity (CAC)” programs are most often applicable to group work (Holt, 1993).

#### 2.6.3. Multifunctional Teams

The elegant design solution is that which meets the maximum requirements with the minimum means, according to Middleton (1967). This means that all relevant factors must be



embraced by the creative act of synthesis called design. This further means that if the factors are so complex and so numerous that a number of specialists are necessary to comprehend them, then all those specialists must be involved, on equal terms, at each stage of decision-making from the very beginning of the process to the very end. Hence there is wide acceptance for new patterns of inter-professional collaboration called multidisciplinary or multifunctional teams.

In design teams, decision-making entails negotiation among parties pursuing common goals with potentially divergent interests and objects according to Bucciarelli (1988). In multidisciplinary design teams, parties negotiate from perspectives further biased by their respective background, expertise, and roles (Brown, Selvaraj, McNeese, Whitaker, 1994).

There is no generally accepted taxonomy of types of teams in either the scholarly or practitioner literature. Teams can be classified according to their autonomy, longevity, purpose, and rank within the organization. Table 2.5, derived from Van Aken's and Kleiner's work (1997) and Scholtes' (1995) work, summarizes various classification schemes:

<b>Hackman</b>	<b>Sundstrom</b>	<b>Dumaine</b>	<b>Cornelius</b>	<b>Scholtes</b>
1. Top management group 2. Task force 3. Professional support group 4. Performing group 5. Human service team 6. Customer service team 7. Production team	1. Advice and involvement 2. Production and service 3. Projects and development 4. Action and negotiation	1. Work team 2. Management team 3. Problem-solving team	1. Standing team 2. Ad-hoc team 3. Natural team	1. Natural work group 2. Business team 3. Executive team 4. Linchpin teams 5. New product and service design teams 6. Process redesign or systems re-engineering teams 7. Improvement project teams

**Table 2.5. Types of Teams (Adapted from Van Aken, 1995)**

The table does not include many other types of teams that are frequently cited in the practitioner literature (e.g., *The Wisdom of Teams* (Katzenbach and Smith, 1993)) including: self-managing teams, autonomous work groups, high performance teams, empowered teams, pseudo teams and many others.

Drucker suggested that there are actually three kinds of teams that are different in structure, in the behavior it demands from its members, in its strengths, its vulnerabilities, its limitations, its requirements and what it can do and should be used for (Drucker, 1995). He classified these using a sports analogy as: baseball teams, football teams, and tennis doubles teams. Teams form in the sports world for several purposes, but primarily because you can play much more complex games with organized groups than you can with individuals (Lentz and Stanford, 1992). In almost every team sport, good teams will beat good talent (Ulrich, 1996).

Baseball teams are composed of players that have fixed positions, play on a team, but rarely play as a team. The sequential engineering process is analogous to a baseball team.

Marketing develops customer needs without input from design. Designers develop product specifications without the assistance of manufacturing. Manufacturing develops the product in isolation from marketing and distribution. There are benefits to the baseball-style team according to Drucker (1995). Each member of the organization can be highly-trained, given goals, and held accountable. All-star baseball teams are usually very successful. Teams organized using the baseball team model can be quite large.

While football teams have players with fixed positions, they play as a team. The concurrent engineering process is analogous to a football team. Marketing, design, manufacturing, and support organizations work together to develop the product. While baseball players can simply play their position to the best of their ability, football players must have a coach to call plays, issue orders, and maintain the rewards system according to Drucker (1995).

On a tennis doubles team, players have a primary position but are expected to “cover” their teammate, adjusting to their teammate’s strengths and weaknesses and to the changing demands of the game, according to Drucker (1995). Rewards are based on the production of the team, not the individual. Team training is important to be a successful team and much time is required before the team is fully functional. Examples of tennis doubles teams are assembly teams on an automotive assembly line, new product development teams, and headquarters executive office teams. Like tennis teams, this type of team is usually quite small having five to seven members at most, according to Drucker (1995).

The engineering literature typically only refers to one type of team in concurrent engineering processes - the multifunctional product development team. Product development teams generally consist of design engineers, production engineers, and personnel from marketing, sales, quality control and other service functions working together (Bisgaard, 1992). Product development teams are sometimes called cross-functional teams due to their makeup. The use of teams creates an opportunity for communication and cooperation and for bringing specialist knowledge into the front of the design process (Evans, 1990). Manufacturing and design people are sitting down together and resolving issues at the earliest opportunity (Nichols, 1992).

Obviously the composition of product development teams are organization, product, and stage of development-specific. No two implementations are the same (Evans, 1990). Team membership changes throughout the process as various aspects of the design are emphasized like features (i.e., marketing influence), quality, reliability, producibility and so on.

Given the above, Salomone (1995) proposed that a typical multifunctional product development team would have the following members: engineering team leader, lead engineering manager, marketing manager, manufacturing engineer, service engineer, information technology specialist, and other key engineering team members (e.g., software engineer, mechanical engineer, qualification engineer, and technology specialist)

Another type of multifunctional team is called a cluster. A cluster is a group of people from different disciplines working together on a semipermanent basis (Snoderly, 1992). Clusters are akin to self-managed teams, but broader. According to Snoderly, clusters are more diverse in composition, being ordinarily composed of persons of different specialties and disciplines. Clusters are large, varying in size from about 30 to 50 members.

Japanese companies manage product development as an overlapping process in which different functional divisions work together in a shared division of labor (Nonaka, Takeuchi,

1995). Some Japanese companies take this a step further. The product development team is divided into competing subgroups that develop different approaches to the design and then argue over the advantages and disadvantages of their proposals. This approach encourages the team to look at the design from a variety of perspectives, eventually developing a common understanding of the “best” approach according to Nonaka and Takeuchi (1995).

#### 2.6.4. Group Size

Group size has been a variable of interest to social-psychologists since the earliest experimental work with groups at the turn of the century (Hare, 1981). Given that teams or groups are the norm in today’s design environment, group size is an important consideration. While abilities, knowledge and skills increase with group size, so do costs (Shaw, 1981). More hands may be available to partition the work of the group but more people increase the potential for organizational problems.

Group size has been a focus of interest in the social sciences for a long time (Bales and Borgatta, 1965). While studies of groups of engineering designers have not been located in the literature, there is no reason to discount the applicability of the large volume of small group research to engineering design groups.

Since the number of potential relationships between group members increase rapidly as a group grows larger (i.e., relationships =  $(n^2-n)/2$ ), larger groups tend to break into subgroups. Larger groups have more resources, lower commitment, require more role differentiation while solidarity is harder to maintain, the average contribution of each member diminishes and it becomes more difficult to reach consensus on a group solution (Hare, 1976; 1992).

Increases in group size tend to be accompanied by increased centralization of authority, increased formality of group operation, increased differences among members in participation and satisfaction, and the need for increased leadership skill for effective group performance (McGrath, 1964). Differences tend to be related to group size in a diminishing returns type of function; that is, a given absolute difference in size (e.g., adding one member) makes more difference for smaller groups than larger groups. Hence, according to McGrath (1964), there are substantial differences between two-person and three-person groups; differences between three- and four-person groups are less sharp; differences between four- and five-person groups are still less.

Three-person groups have special characteristics of intimacy and of power structure (Hare, 1976). In group sizes below five, members complain that the group is too small, although more time is available for interaction. In group sizes above five, members complain that the group is too large due to the restricted amount of participation. A group size of five may be optimum because it has the characteristics that: (1) a strict deadlock is not possible with an odd number of members; (2) the group tends to split into a majority of three and a minority of two, so that being in a minority does not isolate the individual, but allows him sources of gratification; and (3) the group appears to be large enough for the members to shift roles easily and for any individual to withdraw from an awkward position without necessarily having the issue resolved, according to Hare (1976).

The following subsections present the literature on group size as it relates to the following variables: performance, participation, consensus, member reactions, leadership and satisfaction.

#### 2.6.4.1. *Performance*

The effect of size on group performance is the result of two opposing forces. Added resources in larger groups contribute to effective group performance. Increased organizational problems and some members' impulses to contribute tend to decrease the effectiveness of the group (Shaw, 1981).

Steiner's theory of group productivity stated that group productivity depended upon three classes of variables: task demands, resources, and process (Steiner, 1972). According to this theory, group performance should increase with group size when the task is either additive (i.e., the outcome is the result of some combination of individual products) or disjunctive (i.e., the outcome depends upon at least one person in the group performing the task).

In disjunctive tasks performance is determined by the most competent group member. In conjunctive tasks performance is dependent on the least competent member. Productivity on conjunctive tasks generally decreases with group size (Shaw, 1981).

Table 2.6 (Wilke and Meertens, 1994) summarizes the current theory on the relationship between task and motivation, and group productivity.

<b>Task/Motivation</b>	<b>Group Productivity</b>	<b>Description</b>
Additive	Better than best	Group out-performs the best individual
Compensatory	Better than most	Group out-performs a substantial number of group members
Disjunctive (Eureka)	Equal to the best	Group performance matches the performance of the best member
Disjunctive (Non-Eureka)	Less than the best	Group performance can match that of the best member, but often falls short
Conjunctive (Unitary)	Equal to the worst	Group performance matches the performance of the worst member
Conjunctive (Divisible with Matching)	Better than the worst	If subtasks are properly matched to ability of members, group performance can reach high levels
Cooperative	Facilitates group performance	Depends on the cognitive rules of the task
Competitive	Deteriorates group performance	Group performance hampered by competing individual group members
Mixed Mode	Group performance less than optimal	Better than under more competition, but worse than with pure cooperation

**Table 2.6. Group Performance (Adapted from Wilke and Meertens, 1994)**

*2.6.4.2. Participation*

As the size of the group increases, there is a decrease in the overall amount of participation (Shaw, 1981). The amount of time available for each member to participate in the group's activities decreases as size increases. The larger the group the less opportunity each person has to participate. Group members often feel threatened to participate in larger groups.

The distribution of participation varies with group size. Large groups are dominated by a few members while larger proportions of groups members participate less than their fair share (Shaw, 1981). Differences in percentage of total acts among members of three or four persons are relatively small; however, with large groups of five to eight members, the difference between the most active group member and the others increases dramatically.

The quality of the interaction process for a group decision changes with increasing group size as groups use more mechanical methods of introducing information, are less sensitive in the exploration of different points of view, and make more direct attempts to reach a solution (Hare, 1981).

#### 2.6.4.3. *Consensus*

Consensus can be defined as unanimity, simple majority, or a state existing when most of the group has reached a common judgment for which they are willing to show some level of support (Kurstedt, 1993). A consensus decision is one that all members have a part in shaping and that all find at least minimally acceptable as a means of accomplishing some goal (Wood, 1984).

Consensus is a decision method that tends to preserve the small group process, even in groups of considerable size (Hare, 1981). In general, the larger the group the greater the difficulty in obtaining consensus (Shaw, 1981). However, there is pressure toward uniformity and conformity to group standards in large groups. This tends to counterbalance the difficulty in obtaining consensus in large groups. Large groups may have greater resources because they have more members, however, reaching consensus is often more difficult because there are more people expressing divergent opinions (Barker et. al., 1991).

An experiment by Hare in 1952 illustrated the difficulties of reaching consensus in larger groups (Hare, 1976). Groups of five and twelve Boy Scouts played a camping game. The experiment called for members to individually rank items needed for survival, group rank the items, and then individually re-rank the items. The result of the experiment was that as the size of a group increased from five to twelve members, the consensus resulting from group discussion decreased.

While many small groups arrive at a decision by arriving at a unanimous consensus of opinion, little is known about the process by which the group achieves consensus (Godwin, 1974). Godwin proposed four models of the process. Model 1 said that consensus was achieved by random changes of opinion. Model 2 said that each individual had a level of attractiveness and that the probability of shift to a position depended upon the sum of the attractiveness of people at that position. Model 3 said that large subgroups might have an attractiveness disproportionate to their number of members. Model 4 said that the attractiveness of a subgroup depended upon its relative size. The results of the experiment were that larger groups took more time and made more opinion shifts to consensus, for obvious reasons. However, when the number of shifts were divided by the minimum number needed to arrive at consensus, various group sizes were not significantly different and displayed no regular trend.

Two outcomes of this experiment are significant. An individual group member has his greatest effect on other group members while the group is still distributed over a number of different opinions; as soon as subgroups begin to form, the individual member's ability to persuade the group begins to drop sharply. According to Godwin (1974), the best strategy for a group member is to attempt to acquire one or two supporters as early as possible, even perhaps at the cost of some concessions.

Secondly, it was learned that a majority subgroup exerts considerable attraction on other members. Therefore, once a group has arrived at a majority position there may be little required to arrive at a unanimous consensus on the same position.

#### 2.6.4.4. *Member Reactions*

Members of larger groups are less attracted to the group, experience greater tension, and are less satisfied than are members of small groups (Shaw, 1981). Members of small groups express more positive evaluations of their group. As group size increases group members show: greater disagreement, greater antagonism toward others, and greater tension release.

Bray et. al. (1978) conducted an experiment to determine the effects of group size, problem difficulty, and sex on group performance and member reactions. While group size and problem difficulty were important determinants of group performance, member sex generally was not. Bray studied individuals, and same-sex groups of 2, 3, 6, and 10. Smaller groups reported a more positive atmosphere than larger groups, and females rated their group's atmosphere as significantly more positive than did males.

One interesting outcome of the Bray study was that, when asked how many people would be required to solve a similar problem in the future, the preferred and actual number of group members coincide in the range of three to six persons. Bray's study confirmed Steiner's (1972) concept of process losses increasing as group size increased.

#### 2.6.4.5. *Leadership*

There is greater differentiation between the most active person in the group and other group members as the size of the group increases (Shaw, 1981). A leader is more likely to emerge in larger groups than smaller groups. However, large groups make greater demands on the leader and it is more difficult for a randomly-selected member to acquire leadership (Hare, 1981).

There is a greater need for leadership as groups increase in size (Wilke and Meertens, 1994). The coordination and motivation of group members in large groups may become a problem, and this problem may be solved by the installment of a leader. Wilke (1994) stated that a leader is likely to emerge in a number of circumstances. If the task is unlikely to succeed or group outcomes are not allocated in a fair way, a leader may emerge. A number of other things influence whether a leader will emerge including: the persons involved, the type of task, and the type of organization.

Hare's experiment with Boy Scouts also considered the affect of group size on leadership (Hare, 1976). The results of the experiment were that: (1) within groups of the same size, the amount of change in consensus was related to the leader's skill, and (2) the leader in the group of five had more influence on the group decision than the leader of the group of twelve.

Leadership tends not to emerge so clearly in the even sizes below six and not be as identifiable at sizes above six (Hare, 1976). As a result of this finding, members of groups larger than six think of other members in terms of subgroups, or "classes" of some kind, and to deal with members of subgroups other than their own by more stereotyped methods of response.

Leadership on cross-functional teams passes back and forth from person to person as the phases of the project succeed one another and different skills become critical (Bridges, 1996). The leaders of teams must also know when to follow (Smith, 1996). No one person can possibly master all the divergent sources of information necessary to make good decisions (Ulrich, 1996).

#### 2.6.4.6. *Satisfaction*

Members in small groups are more likely to be satisfied than members in large groups (Hare, 1976). Members of larger groups are significantly less satisfied with the amount of time available for discussion, with their opportunity to participate, and with the group meeting or its decision (Thomas and Fink, 1965).

#### 2.6.4.7. *Summary*

What is the optimum group size? The literature shows no clear agreement on this issue. Many scholars believe that five to seven members is the optimum size for small groups (Napier and Gershenfeld, 1989). Holloman and Hendrick's study (1971), discussed previously, showed that six was the optimum number. However, clearly the task of the group and its goals affect the optimum size (Barker et. al., 1991). Barker (1991) offered that a group should be just large enough to include individuals with all the relevant skills necessary to solve the problem, yet small enough to provide opportunities for individual participation.

### 2.6.5. Measurement of Group Dynamics - SYMLOG

#### 2.6.5.1. *Introduction*

SYMLOG is an acronym for *SY*stematic *MU*ltiple *LE*vel *O*bservation of *G*roups (Bales and Cohen, 1979). According to Bales and Cohen, SYMLOG is:

*“A set of methods for the study of groups - groups of many kinds, but basically small natural groups, such as families, teams, or classroom groups, where the personalities of the specific persons involved and their relationships with each other are the focus of interest.”*

SYMLOG is a system for the study of groups in the sense that it consists of a number of parts, integrated to make a particular group easier to understand and work with. SYMLOG does not require any special equipment. It can be applied by a single person by the completion of a SYMLOG Adjective Rating Form (see Appendix D.6.2.). On this form is recorded the characteristic observed behavior of any group of individuals.

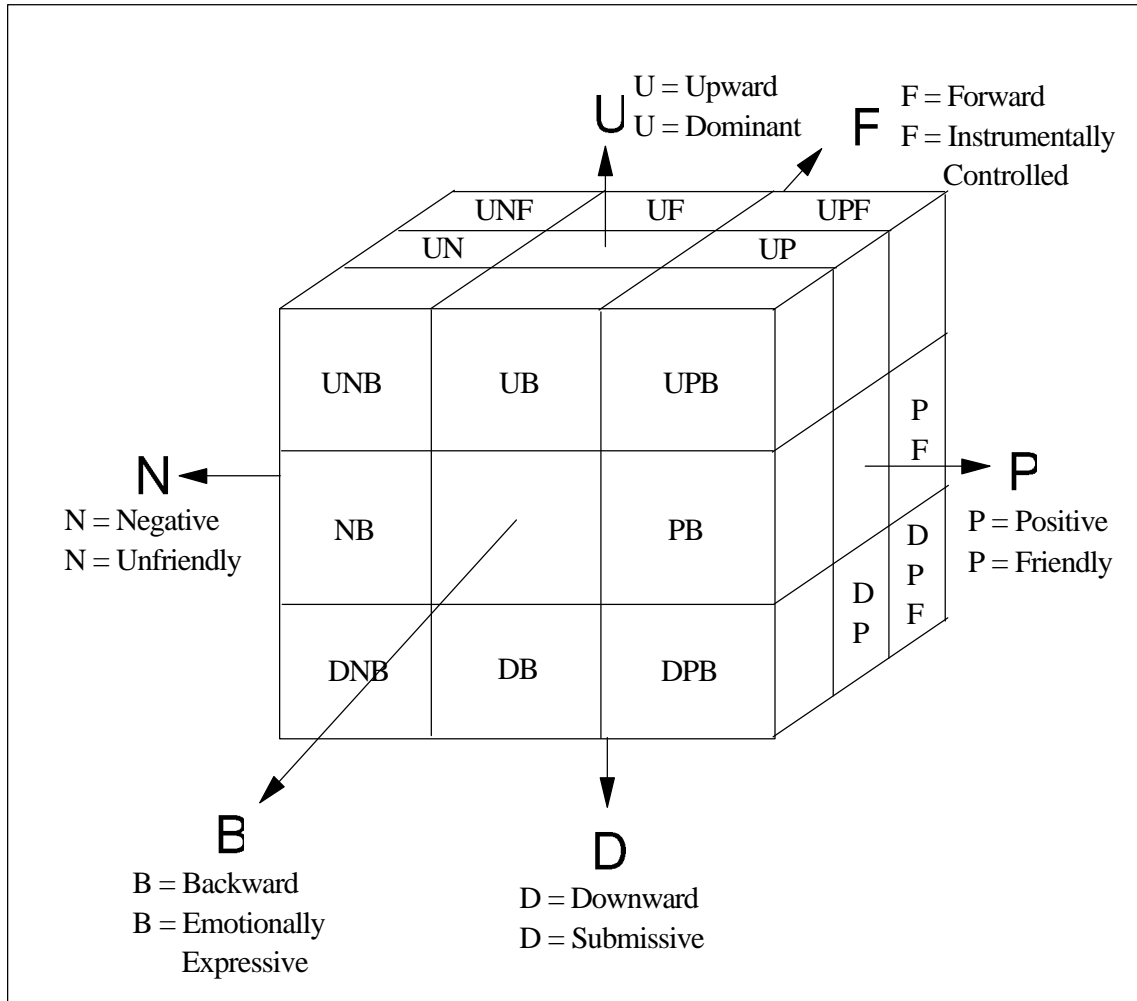
In SYMLOG, all behavior and content in the interaction of a group is described by reference to a concept of a three-dimensional space. The three dimensions, which describe the quality of the behavior of members, or the content of what they say are: (1) Dominant versus Submissive, (2) Friendly versus Unfriendly, and (3) Instrumentally Controlled versus Emotionally Expressive. In the SYMLOG rating procedure, each individual member of the group is rated separately, on the basis of observation of his or her behavior or image content. This information can be summarized to the group level to determine the overall orientation of the group.

The SYMLOG three-dimensional space is shown in Figure 2.7. Each location or class of directions is defined by the logical combinations of the six named reference directions. The directions are named from a reference point at the intersection of the three dimensions, looking forward.



SYMLOG interaction scoring of a video tape is the preferred method as contrasted with retrospective rating because it probably tends to reduce the effects of the researcher's particular biases and selective memory. Recordings do have the disadvantage of requiring considerable time to analyze.

According to Bales and Cohen, SYMLOG is a uniquely comprehensive and highly integrated system for the study of the behavior of individuals in groups having strong theoretical origins and implications.



**Figure 2.7. The SYMLOG Three-Dimensional Space (Adapted from Bales and Cohen, 1979)**

#### 2.6.5.2. Theory

SYMLOG's theoretical basis has many connections to the fields of personality study, clinical psychology, and individual and group psychotherapy, as well as the fields of group training, organization development, social group work, and family therapy (Bales and Cohen, 1979). According to Bales and Cohen (p. 11):

*“The assumptions made in the present work about motivation, the general nature of personality, the powers of the ego, and the importance of the various mechanisms of ego defense, as well as many of the concepts of the nature of interpretation and its place in therapy come from psychoanalytic theory. The concepts of the nature of the individual perceptual evaluative field have their source partly in gestalt psychology, as represented in both Lewinian field theory and the group dynamics school. The theory of polarization and unification is closely related to various theories of social cognition: balance theory, congruity theory, dissonance theory, consistency theory, and attribution theory, although the relationships to these various cognitively oriented theories are complex and far from adequately worked out.”*

SYMLOG also has connections to a number of sociological theories according to Bales and Cohen (1979). SYMLOG has much in common with symbolic interaction theory in the emphasis given to the importance of the self-image and the individual definition of the situation, and in the stress on the communication of meaning in the manner and content of social interaction. Small group interaction theory provides many of the concepts of role differentiation, leadership, and small group structure in other respects, as well as groundwork in the actual observation and classification of social interaction.

Social exchange theory is represented in the concepts that the behavior and content presented to each other by the participants in interaction constitute rewards and punishments or have both benefits and costs. The relativistic nature of the costs and benefits is derived from reference group theory and in social evaluation theory.

Lastly, there is a theoretical conflict in general sociology as to how much emphasis should be given to the influence of common values and norms of participants and how much to the conflicts of interest between the various participants and to differences in their relative power. This is often represented as a conflict between adherence to structural-functional theory and adherence to conflict theory. SYMLOG is able to consider the two empirically.

Bales and Cohen (1979, p. 13) provide the following summary of the theory of SYMLOG:

*“The theory of SYMLOG gives emphasis equally to the dynamics of groups and to the dynamics of individual personalities of group members. It gives an articulate way to get back and forth from a consideration of each individual personality to a consideration of the dynamic field properties of the total group-and-situation constellation.”*

#### 2.6.5.3. *Applications*

Given the over 30-year history of SYMLOG, it is not surprising that there have been hundreds of applications of the technology in a variety of settings for many different purposes. Teachers, counselors, consultants, facilitators, strategists, therapists, managers, or group members often need to assess group functioning (Polley and Stone, 1988). They want to know how individual group members contribute to a group's dynamics. They want to assess how group dynamics relates to its creativity, productivity, and cohesiveness. They want to be able to predict the impact of change on a group's dynamics.

There are many applications of SYMLOG in educational settings (e.g., secondary classroom management), social work (e.g., counseling), group and family therapy, individual psychotherapy, and international relations. The prime area of relevance to this research is the use of SYMLOG in organizational settings. According to Bales (1988), studies in the use of SYMLOG in business and industrial organizations are the most numerous with projects having been conducted by Koenigs, Cowen, Poumadere, Polley, Hogan, Kaftan, Isenberg, Hare, Edelman, Maddocks, Williamson, Barnes, Goodpaster, Barnes, Kriger, and Vanneman. However, a review of over 100 citations relating to SYMLOG projects did not reveal any related to engineering or highly-technical organizations. There is no reason to believe that SYMLOG would not be applicable for analysis of technically-oriented groups.

### 2.7. **Research Problem**

This literature review confirms that the research proposed herein is unique. Sociotechnical systems theory has not been applied to the organizational design of an engineering design function. Clearly from a theoretical standpoint, it is applicable. Previous macroergonomic interventions have also not been applied in the domain of engineering design.

This review has shown that engineering design is a very important function having implications for international competitiveness. It has also been shown that the state of the art of theory in design is still very immature. Major innovations in processes, concurrent versus sequential engineering, and technology, CSCW, are presenting opportunities for major improvements in the design process. Simultaneously, we have learned the importance of team social constructs in product development and decision-making.

Previous research in engineering is deficient with respect to the joint consideration of technological and personnel factors. Previous research in groups has generally ignored the engineering design area, as has computer-supported cooperative work research. This research, targeted at the intersection of engineering methodology, group size, and the use of computer-supported cooperative work, will extend our level of understanding of these factors. The joint optimization of these technological and personnel variables demonstrates the value of STS in a new domain, and validates or confirms group and CSCW research in engineering.

### 3. Research Methodology

#### 3.1. Overview

The following summarizes the questions asked in this research:

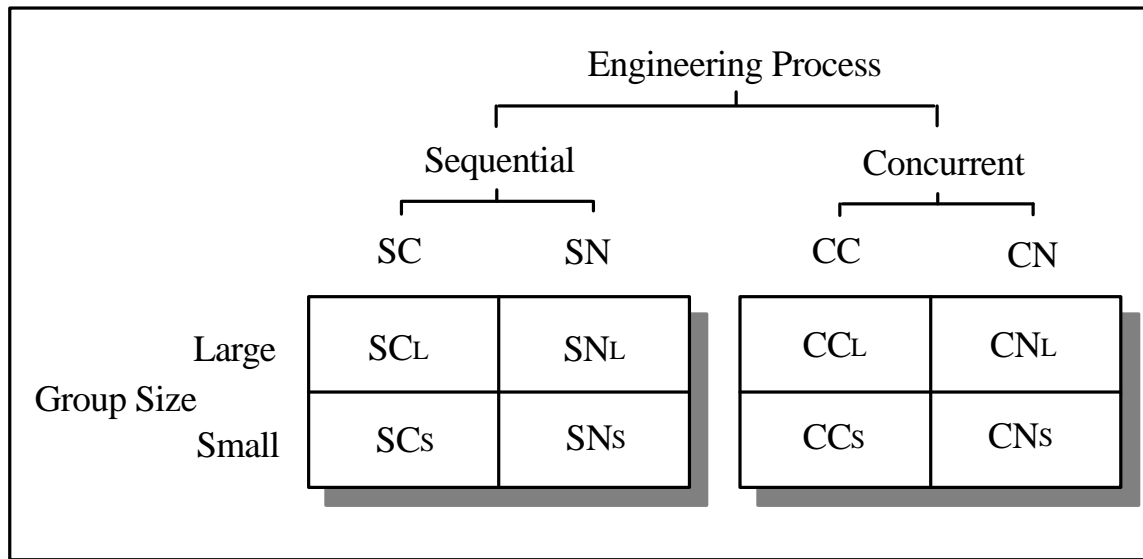
- *Research Question 1* asked how design performance is affected by engineering methodology, group size, or computer support.
- *Research Question 2* asked how process time is affected by engineering methodology, group size, or computer support.
- *Research Question 3* asked how process cost is affected by engineering methodology, group size, or computer support.
- *Research Question 4* asked how the satisfaction of group members toward the engineering design decision process is affected by engineering methodology, group size, or computer support.
- *Research Question 5* asked if there was a optimum combination of engineering methodology, group size, and computer support that creates the greatest technical and social outcome.

The research methodology consisted of two phases. The first phase of the research methodology was a laboratory experiment using engineering and building construction students in a controlled setting. This phase was designed to establish causal relationships. In the second phase, the results of the experiment were provided to recognized industry and academic experts in the engineering design process for their comment. The purpose of this phase was to provide external validity to the results obtained in the laboratory.

##### 3.1.1. Experimental Design

The experimental design of this research was a 2 x 2 x 2 factorial, between subjects design (see Figure 3.1). The two levels of the engineering methodology variable were sequential and concurrent engineering. The two levels of the group size variable were large teams, consisting of six students, and small teams, consisting of three students. The two levels of the computer support variable were using and not using groupware.

Each team was given a set of requirements to design a transportation system that moved a payload from one point to another. Each team was asked to: (1) develop a design concept, (2) develop a detail design in the form of engineering drawings, (3) manufacture the system based on their design products (e.g., drawings and specifications) using toy plastic LEGOS, and (4) test the system to determine if it met the design requirements.



**Figure 3.1. Experimental Design**

There were five teams per condition. The determination of the number of teams tested in each treatment (i.e., sample size) was an important issue. Enough teams were needed to create statistical confidence in the outcomes. However, there were practical considerations relating to the availability of participants. Note that teams were the unit of analysis rather than individuals in this experiment.

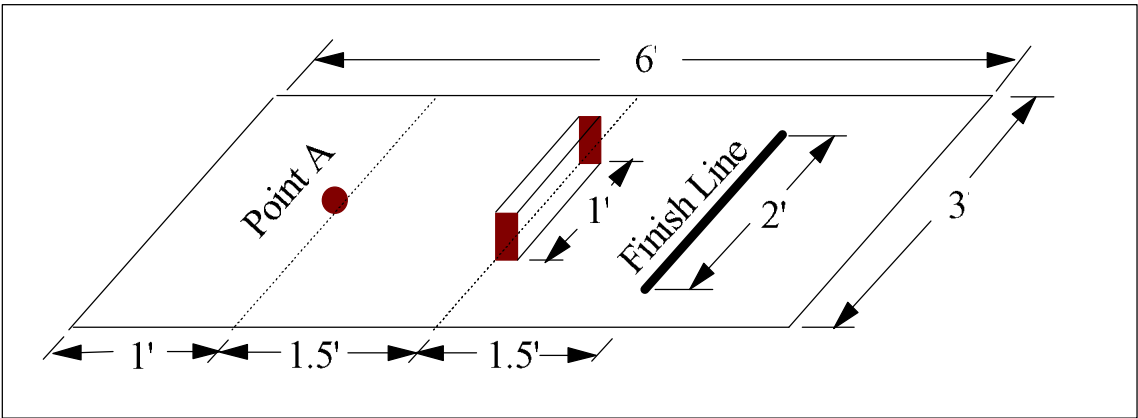
Hinkelmann and Kempthorne (1994) provided a methodology based on determining the minimum difference between the two extreme treatments, the best and the worst, that detects, with probability of at least  $1 - \beta$ , that such a difference exists. Assuming that  $1 - \beta = 0.8$ , five teams would provide a desired goal of 2.5 standard deviations using tables developed by Bowman and Kastenbaum in 1975. Therefore, five teams were used in each of the eight treatments. This required 180 subjects. The rationale for five teams was to achieve a balance between the number of trials needed for statistical significance and the overall availability of participants.

Team members were equally divided into three functional disciplines: design, manufacturing, and support. Training was provided to the participants to perform as members of each functional discipline. As described later, members were given the following functional goals that they were told to advocate in each design task:

- Design: Maximize the robustness of the system in conceptual design. Minimize the time required to complete conceptual and detail design.
- Manufacturing: Minimize the volumetric cube of the final system in conceptual design. Reduce the number of unique component parts in detail design.

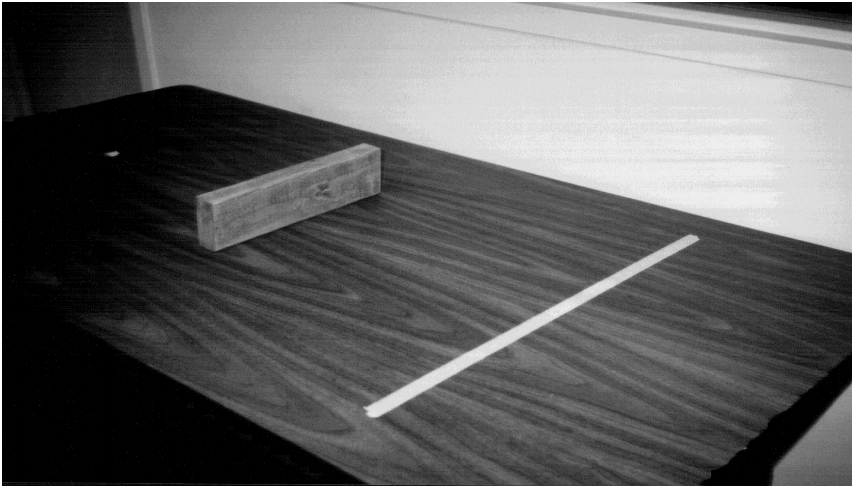
- Support: Minimize the number of moving parts in conceptual design.  
Minimize the life-cycle cost of the system in detail design.

The task was to design a robust system, using LEGOS, for moving a ping-pong ball, the payload, sitting on a small LEGO piece (5/8 x 5/8 x 3/8 inch), from a designated starting point across a target finish line that was 2 feet long and 3 feet away as shown in Figure 3.2. There was a hurdle half way between the starting point and parallel to the finish line that consisted of a one foot long 2" x 4" board (actual dimensions = 1 1/2" x 3 1/2") oriented as shown. The ball could have been moved over or around the hurdle. The initial energy to move the ball had to be either kinetic (e.g., from a LEGO motor) or potential (e.g., a rubber band held in tension). There could be no human interaction in moving the ball once the process commenced.



**Figure 3.2. Experimental Setup**

Figure 3.3 shows a photograph of the actual setup in the laboratory.



**Figure 3.3. Actual Laboratory Setup**

The initial requirements for the system stated that the system should be robust. In other words, the system designed should be capable of achieving its mission with minor changes in the specifications. Only designs that fully met all requirements were evaluated for robustness. Robustness is a characteristic of the quality of the design (Parsaei and Sullivan, 1993). Robustness means that the design functions beyond the range of conditions that are likely to be met (Clausing, 1994). In this case, systems were evaluated using a golf ball in addition to the ping-pong ball specified in the requirements, if the system met all of the original specifications.

### **3.2. Subjects**

All participants in this research were selected to have the following characteristics:

- Age: No restriction. Age was not likely to be a factor in the performance of this experiment.
- Gender: Male or female. Gender was not likely to be a factor in the performance of this experiment.
- Education: Subjects were Freshmen, Sophomore, Junior, Senior, or graduate students majoring in engineering, or building construction. Subjects at this level of education had courses in design, CAD, and, likely possessed a mechanical aptitude.
- Computer Literacy: Subjects possessed a general knowledge of the Windows environment
- CAD Literacy: At least one person on each team had a working knowledge of computer-aided design software, preferably AutoCAD.
- Familiarity: It was not desirable for subjects to be a team prior to the conduct of the experiment.

All participants were given a brief training exercise in AutoCAD, assembly of systems from three-view drawings, life-cycle cost, and the use of LEGOS.

### **3.3. Materials and Equipment**

#### 3.3.1. Materials

All teams had the following materials to work with: a Technic II set of LEGOS, a set of standard LEGOS (Set 114 and Set 1715) with 400 pieces, rubber bands, a roll of Scotch-brand tape, a 4" x 7" piece of cardboard, a calculator, six #2 pencils, paper, a pocket rule, and scissors.

The experimental equipment included a ping-pong ball sitting on a 3/8" LEGO piece (5/8 x 5/8 inch), a one foot long 2" x 4" board, a 2' long piece of tape, and a 3' x 6' table upon which to conduct the testing of the system.

All teams had access to personal computers connected to the campus network, running Windows 95, AutoCAD Release 13 software for computer-aided design, WORD for word

processing, and EXCEL for spreadsheet software. In addition, computer-supported teams had access to group support systems software as described below.

### 3.3.2. Groupware

The software that was used to by computer-supported cooperative work teams was GroupSystems, a product of Ventana Corporation. GroupSystems is a powerful line of group-enabled group decision support software products that can be used for a number of functions including: re-engineering, strategic planning, quality improvement, education, product design, and process improvement.

There are a number of benefits of using GroupSystems software according to Ventana's product literature. *Simultaneous input* leverages the team's time and creates better quality ideas. *Anonymous participation* encourages insightful comments without fear of reprisals. *Instant documentation* automatically records every idea for distribution and future work. *Process support* facilitates movement from Point A to Point B in a team process. *Access to information* lets the group use outside information while working in GroupSystems.

The following tools were available within the software that could have been used in this experiment. *Categorizer* allows the group to generate a list of ideas and supporting comments. Categories are created for the ideas, and participants can drag the ideas into the desired category. *Electronic Brainstorming* provides a simple process in which a question or issue is distributed to participants, who respond with comments. It promotes creative and far-reaching discussions about the same issue. *Group Outliner* allows the group to create and comment on a multi-level list of topics. Levels of subordination are represented by structure lines, bullets, or a legal numbering format. *Topic Commenter* allows participants to comment on a list of topics. This tool's format for idea generation is more structured than Electronic Brainstorming, but less structured than Group Outliner. *Vote* provides a variety of methods with which the group can evaluate a list of ideas. Voting methods available include Rank Order, Multiple Selection, 4-Point and 5-Point Agree/Disagree, 10-Point Scale, Yes/No, True/False, and user-defined Custom method. The results can be displayed in statistical and graphic formats.

*Categorizer* and *Vote* were the only tools used in this experiment. *Categorizer* was used because it most closely permitted a nominal group technique to be simulated during idea generation and consolidation/clarification of concepts. *Vote* was used to simulate voting in a manual nominal group process.

### 3.3.3. Computer-Aided Design Software (AutoCAD)

AutoCAD is the current computer-aided design software that Virginia Tech students are taught as Freshmen. AutoCAD is a product of Autodesk, Inc., the world's leading supplier of computer-aided design software. AutoCAD has an installed base of over three million customers. Autodesk is organized around five key market groups that closely match its diverse customer base: Architecture, Engineering, and Construction; Mechanical Computer-Aided Design; Geographic Information Systems; Data Management; and Multimedia.

AutoCAD incorporates one of the most comprehensive two-dimensional and three-dimensional drafting feature sets available. External reference capabilities permit the linking of detail drawings or blocks to master drawings. AutoCAD has excellent documentation, on-line



context-sensitive Help, and a modern, customizable user interface which all enhance AutoCAD software's accessibility and ease of use.

This experiment used Release 13c4 of AutoCAD. All LEGO pieces had been previously modeled as two-dimensional objects by the researcher prior to the conduct of the experiment. This greatly reduced the time required for drawing. This represents the conditions likely to be encountered in industry where parts have been developed into a CAD library of standard parts.

### **3.4. Facilities**

The Macroergonomics and Group Decision Systems Laboratory in Whittemore Hall was used by all teams. This laboratory, Room 567, had six workstations, a server, a whiteboard, videotaping capability, and a one-way mirror for observation. The view of the room from the control room is shown in Figure 3.4.



**Figure 3.4. Photo of Macroergonomics and Group Decision Systems Laboratory in the Human Factors Engineering Center**

### **3.5. Experimental Design**

#### 3.5.1. Justification of Experimental Methodology

There are methodological weaknesses in the standard research methodologies of laboratory experiments, case studies, action research and surveys. Bowen (1995) suggested the relative strengths and weaknesses of the various methods as shown in Table 3.1. He also noted that, “ internal validity is a concern and goal for all of the methods, and with careful design a ‘high’ rating is feasible in all cases and hence is not included as a column in the table. Internal validity may be slightly easier to obtain in survey and experimental research, where pre-testing and

iterative designs are practical, and harder to obtain in case study research where pre-testing may be more difficult.”

Bowen further stated that, researchers must provide their own preferential weighting to the dimensions shown in the table, based on the research questions being addressed, time and other resource constraints, to determine which method best suits their particular requirements.

Research Method	Ability to Make Causal Inferences	External Validity	Opportunity to Study a Large Number of Groups	Degree to which Cooperation of External Work Organizations(s) is Required	Opportunity for Longitudinal (versus cross-sectional) Studies	Theory Building
Laboratory Experiment	High	Low	High	Low	Low	Medium
Case Studies Natural	Low	Medium	Low	High	Medium	High
Case Studies Action	Medium	Medium	Low	High	Medium	Medium
Survey	Low	High	High	Medium	High	Low

**Table 3.1. Relative Strengths and Weaknesses of Standard Research Methodologies**

In the context of this research, the most important goal was to establish causality. Laboratory experiments are rated highest in this category. Previous attempts to study concurrent engineering by case study and survey methods have been criticized due to the inability of the researchers to isolate the effects of concurrent engineering from other process improvements or interventions occurring at the same time. Some of the other confounding improvements included implementation of Total Quality Management, quality circles, union labor concessions, and market expansion.

While a laboratory experiment is considered low in external validity, Bowen advocated the use of engineering students in laboratory experiments. The use of a laboratory experiment with engineering and building construction students, coupled with a field analysis of the results of the experiment, provided a strong combination of approaches to establish causality and increase external validity.

The laboratory experiment, as well as survey research, is rated high in the opportunity to study a large number of groups. While it might be easier to study a larger number of groups using survey research, the data would be subjective rather than objective. In the context of this experiment it would be difficult to find a large number of groups that are comparable.

The laboratory experiment was also preferable because it required the lowest degree of cooperation of external work organizations. The identification and subsequent commitment of external organizations would have been quite time-consuming and subject to high risk of continuance with the experiment.

The laboratory experiment has a low opportunity for longitudinal study. However, this is not considered important in this experiment because of the specific nature of the rapidly evolving technology related to CSCW technology.

And finally, while the laboratory experiment does not offer as high an opportunity for theory building as a natural case study, it is as high as the other methods.

The laboratory experiment was particularly important for the aspect of this experiment related to CSCW. Gallupe, DeSanctis, and Dickson (1988) argued that at this very early stage of CSCW research, an experiment offers many advantages. It builds on existing research that has used the experimental method. In the laboratory setting the researcher can carefully manipulate the characteristics of the task and measure the effects of CSCW on group decision processes and outcomes, while controlling the extraneous variance. These variables would be difficult to manipulate or measure carefully in a field setting. A large number of research participants are needed for statistical power which makes students an attractive subject pool. And finally, given that the effects of CSCW on performance and attitude are largely unknown, there is reluctance to expose live organizational groups to the technology without controls.

### 3.5.2. Pilot Testing

There existed a large number of approaches to a feasible solution to this problem, thus providing a range of alternatives for consideration by the teams. Therefore, a key component of this experiment was pilot testing of the task prior to conducting the experiment.

For this research to be successful, the experiment chosen must have had a degree of difficulty that made it non-trivial, but solvable within the time constraint chosen for this experiment (three hours). Difficulty is a relative term that could only be determined by pilot experiment.

The first phase of pilot testing, alpha testing, consisted of a series of structured walk-throughs of the entire experimental process. The purpose of alpha testing was to ensure that all instructions to participants were unambiguous and complete. Alpha testing also confirmed that data collection processes and forms were complete. There were four separate alpha tests conducted.

The second phase of pilot testing, beta testing, was conducted with participants that met the participant requirements. The purpose of beta testing was to ensure that the system design problem was properly structured to be solvable with time constraints. Beta testing also validated the computer support component of the experiment. Software was tested and all software issues resolved. The final aspect of beta testing was to ensure that all data collection processes were tested.

The experimental setup for pilot testing was identical to the actual testing. Pilot testing verified that all data that needed to be collected could be collected and analyzed as predicted.

Concurrent with pilot testing, industry and academic experts were consulted to determine whether they concurred with the experimental methodology, and whether they believed that the experiment represented the engineering environment that was being addressed as accurately as possible.

Dr. Ed Haug, Director of the Center for Computer Aided Design at the University of Iowa was consulted. Dr. Haug was the primary author of *CALS Technical Report 002 - Application of*

*Concurrent Engineering to Mechanical Systems Design*. Dr. Haug is a recognized leader in the development of integrated design tools.

Ms. Naomi McAfee, formerly Director of Reliability and Maintainability with Westinghouse was consulted. Ms. McAfee co-chaired the CALS Industry Steering Group's Concurrent Engineering Task Group with the researcher for ten years.

### **3.6. Procedure**

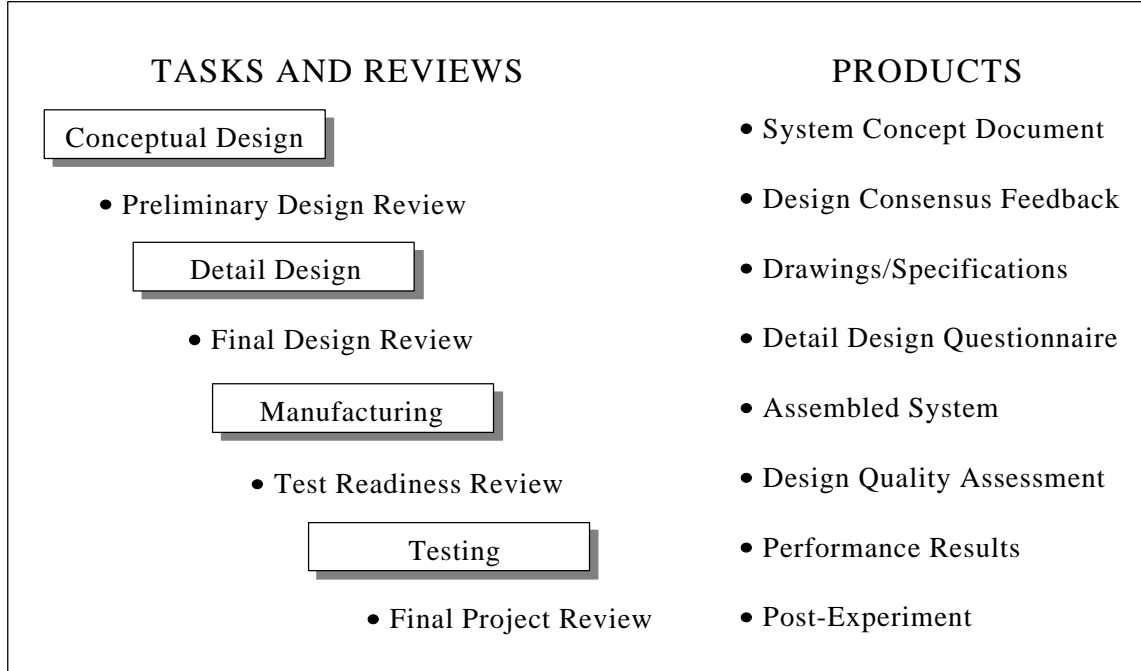
In the laboratory experiment phase of this research, 40 teams comprised of 180 participants performed the experiment. Students were obtained from undergraduate and graduate classes in industrial engineering and building construction that considered design, manufacturing, logistics, or organizational issues. Students were randomly assigned to three and six person teams and treatment conditions. The first person assigned to each team had to have AutoCAD experience.

Institutional Review Board (IRB) approval was received to conduct the experiment. Students agreeing to participate in the research signed the IRB consent agreement (Appendix A) and agreed not to disclose the nature of the experiment to others. The procedure for assigning teams to treatments is provided in Appendix B. Students were also randomly assigned to one of three functional roles --- design, manufacturing, and support. The number of students in each role were the same on each team.

All participants confirmed that they met the requirements described in Section 3.2. and provided additional demographic data.

### 3.6.1. Experiment Overview

The experiment consisted of the design tasks and reviews as shown in Figure 3.5. Each task and review produced measurable data that was used in the analysis phase of this research.



**Figure 3.5. Definition of Design Tasks and Products**

Prior to the beginning of the experiment each team was briefed on the nature of the experiment. They were not informed about the subjects being researched. Each person was given a set of materials from which the design must be manufactured. They were told that they had unlimited time to complete the task, but time was of the essence and an important factor in calculating the performance of the team.

All teams were given four brief training lectures and exercises to establish a sufficient level of proficiency in: (1) the use and manipulation of technical LEGOS, (2) AutoCAD, (3) interpreting three-view drawings, and (4) life-cycle cost.

Teams were told that the objective of the experiment was to design a robust system that will successfully achieve the requirements of the system (i.e., move the ping-pong ball across the finish line).

The researcher was available to respond to questions throughout the conduct of the experiment but will did not act as a leader of the team and did not participate in the task process.

Videotapes were made of all experiments. Tapes were used to collect data that could not be collected in real time. The use of videotapes in this type of experiment is routine and is quite helpful in the post hoc reduction of data. Tapes will be stored for one year after the conclusion of the experiments and then destroyed.

The following sections describe each task and review. A copy of the researcher's script for the conduct of the experiment is provided in Appendix C.

### 3.6.2. Conceptual Design

Conceptual design commenced with the distribution of the System Performance Requirements Statement (Appendix D.1.1) and concluded when the team reached final consensus, defined to be member acceptance, on a feasible approach. The products of conceptual design were a brief textual description of the approach on the Design Concept Form (Appendix D.1.5) and a rough sketch of the system on a 11" x 17" System Concept Diagram (Appendix D.1.6).

Sequential engineering teams were given functional goals for design, manufacturing, and support serially (Appendix D.1.4). Teams reached agreement on a concept based on the design functional goals. They were then given manufacturing goals and given the opportunity to change their conceptual design. After they reached agreement they were then given support goals and asked to reconsider their conceptual design in that context. Concurrent engineering teams were given all functional goals at the start of conceptual design.

Teams that were provided computer-supported work technology were required to use group systems support software employing an automated nominal group technique process. Teams not provided computer support used a manual nominal group technique led by the researcher.

### 3.6.3. Preliminary Design Review

At the conclusion of conceptual design, a Preliminary Design Review (Appendix D.1.7) was conducted. The purpose of the preliminary design review was to initiate the capture of process data using survey research techniques. Each individual completed a Preliminary Design Review survey. The design review survey captured data related to: individual confidence in their design decision, leadership of the team, individual perspective of the contributions of others, individual perspective on whether each team member achieved their functional goals, the degree of support for the team's decision, individual perception of conflict on the team.

For those teams using groupware, the survey asked additional questions regarding: the ease of use of groupware, groupware's impact on efficiency, effectiveness, and productivity, groupware's impact on the contribution of team members and the individuals level of satisfaction with the groupware process.

The use of self-reporting measures, like a survey, are appropriate when the people whose attitudes are being investigated: (1) are able to understand the questions asked of them, (2) have sufficient self-awareness to provide the necessary information, and (3) are likely to answer honestly and not deliberately falsify their responses (Henerson, Morris, Fitz-Gibbon, 1987).

All of the reviews were constructed using a Likert five-point scale (Likert, 1952) with values of one equaling "strongly agree" to five equaling "strongly disagree". This scale was used consistently throughout the experiment. Questions were constructed so that persons with different points of view would respond to it differentially. Questions were worded in clear, concise, straight-forward statements. Only a single variable was addressed in each question. According to Likert, this is the desired approach to developing a survey.

#### 3.6.4. Detail Design

Teams were asked during the detail design phase to develop a set of instructions that could be used to build a system that would achieve the requirements of the system. Those instructions consisted of drawings, sketches, and/or text.

Sequential engineering teams were given functional goals for design, manufacturing, and support (Appendix D.3.1) serially as in conceptual design. Concurrent engineering teams were given all functional goals at the start of detail design.

All teams used the AutoCAD computer-aided design software for production of a one-view drawing of the system or subsystem that interfaced with the ping-pong ball. Other drawings and sketches were drawn manually. All teams were given use of Microsoft EXCEL spreadsheet and Microsoft WORD word processing software for Windows '95.

#### 3.6.5. Final Design Review

At the conclusion of detail design, a Final Design Review (Appendix D.3.2) was conducted in the same manner as the previous review. This design review survey captured data related to: individual confidence in their design decision, leadership of the team, individual perspective of the contributions of others, individual perspective on whether each team member achieved their functional goals, individual perspective on whether design, manufacturing, or support influenced the design process, individual perspective on whether he/she achieved his/her functional goals, and individual perception of conflict on the team.

#### 3.6.6. Manufacturing

The manufacturing member(s) of the team constructed the system based on the team's manufacturing instructions developed in detail design. The manufacturer(s) were instructed to not make any intuitive decisions on the materials that he or she was given.

After the manufacturer(s) completed assembly of the design, the product was reviewed by the team for compliance with their design intent. Errors caused by the quality of the instructions were recorded by the team. The team was asked to document all defects in the instructions on the Design Errors and Defects Form (Appendix D.4.1) with respect to accuracy and completeness. The manufacturing phase concluded when the team declared that the system was ready for testing.

#### 3.6.7. Test Readiness Review

Data related to process issues was generated during the Test Readiness Review (Appendix D.4.2) in the same manner as in previous reviews. Questions in this review concerned: individual confidence in their design, individual view of whether the team had designed as good a system as they were capable of designing, and individual perspective of the contributions of others.

### 3.6.8. Testing

The team was given three attempts to use their system to achieve the requirements of the system. Each attempt's outcome was recorded by the researcher. Teams were allowed to rebuild their systems to the original specifications if they were damaged in testing. If the system was successfully tested three times the research declared that the team had performed successfully and announced that the design would be tested for robustness. Testing was repeated with a golf ball rather than a ping-pong ball. The outcomes were recorded; however, there was no opportunity for redesign between trials to improve the results.

### 3.6.9. Final Project Review

At the conclusion of testing, a Final Project Review (Appendix D.5.2) was conducted to collect team learning from the experiment. The final project review is a narrative response, completed by the team, not individuals, to collect textual data relating to what the team would have done differently had it been as knowledgeable at the start as it was at this stage.

Team members were then asked to complete an Individual Post Experiment Questionnaire (Appendix D.5.3), that measured each individual's perspective on a number of process issues. Questions in this review related to: individual confidence in the design, process satisfaction in both conceptual and detail design, contributions by all members of the team, conflict, degree of agreement with the final system, leadership, previous familiarity with team members, perception of the importance of AutoCAD to engineering design, and process satisfaction. A final question required the individual to describe the overall strategy that the team used to solve the problem.

Participants were then asked to complete a Team Post Experiment Questionnaire (Appendix D.5.4) as a team. This survey was designed to repeat many of the questions from the individual survey in order to be able to assess the congruence between the individual and team responses. Questions in this review related to: individual confidence in the design, process satisfaction in both conceptual and detail design, contributions by all members of the team, conflict, and degree of agreement with the final system.

### 3.6.10. Field Critique

Causality is the goal of the laboratory experiment. The goal of the field critique was, by acquiring industry feedback on the results of the experiment, to increase external validity of the results. The combination of laboratory testing followed by field critique adequately answered the research questions.

The results of the experiment were summarized into an overview of findings. Findings emphasized the "why" of what happened and was learned in the experiment. This information was provided to recognized industry and academic experts in the engineering design process in the form of a survey instrument. These experts were also asked to provide information from their experience that either affirms or refutes the findings. A list of the experts and copy of the survey instrument is provided in Appendix F.



### 3.7. Data Collection and Analysis

#### 3.7.1. Data Collection

Table 3.2 shows the elements of data that were collected as a function of project phase and data that was calculated:

**Table 3.2. Data Element List**

<b>Data Element</b>	<b>Purpose</b>	<b>Collected By</b>	<b>Where Logged</b>
<b><i>CONCEPTUAL DESIGN</i></b>			
CD Process Time	Calculate Total Process Time and Design Time	Researcher	Time Card, LCC, and Researcher's Log
Ideas	Analyze Process	Researcher	Researcher Log
Final Ideas	Analyze Process	Researcher	Researcher Log
Comments	Analyze Process	Researcher	Researcher Log
Design Confidence	Analyze Process	Team	PDR Survey
Leadership	Analyze Process	Team	PDR Survey
Team Contribution	Analyze Process	Team	PDR Survey
Functional Achievement	Analyze Process	Team	PDR Survey
Design Support	Analyze Process	Team	PDR Survey
Team Interaction	Analyze Process	Team	PDR Survey
Groupware Ease	Analyze Process	Team	PDR Survey
Groupware Efficiency	Analyze Process	Team	PDR Survey
Groupware Effectiveness	Analyze Process	Team	PDR Survey
Groupware Productivity	Analyze Process	Team	PDR Survey
Individual Contribution	Analyze Process	Team	PDR Survey
Groupware Satisfaction	Analyze Process	Team	PDR Survey
<b><i>DETAIL DESIGN</i></b>			
DD Process Time	Calculate Total Process Time and Design Time	Researcher	Time Card, LCC, and Researcher's Log
Design Confidence	Analyze Process	Team	FDR Survey
Leadership	Analyze Process	Team	FDR Survey
Team Contribution	Analyze Process	Team	FDR Survey
Functional Achievement	Analyze Process	Team	FDR Survey
Life Cycle Influence	Analyze Process	Team	FDR Survey
Manufacturing Influence	Analyze Process	Team	FDR Survey
Design Influence	Analyze Process	Team	FDR Survey
Personal Goals	Analyze Process	Team	FDR Survey
Team Interaction	Analyze Process	Team	FDR Survey
AutoCAD Tutorial Time	Analyze Process	Team	FDR Survey
Manufacturing Tut. Time	Analyze Process	Team	FDR Survey
LCC Tutorial Time	Analyze Process	Team	FDR Survey
<b><i>MANUFACTURING</i></b>			
MFG Process Time	Calculate Total Process Time	Researcher	Time Card, LCC, and Researcher's Log
Design Errors	Analyze Process	Team	Design Defects Form
Manufacturing Errors	Analyze Process	Team	Design Defects Form
Design Confidence	Analyze Process	Team	TRR Survey

Design Assessment	Analyze Process	Team	TRR Survey
Member Contributions	Analyze Process	Team	TRR Survey
Level of Confidence	Analyze Process	Team	TRR Survey
<b>TESTING</b>			
TT Process Time	Calculate Total Process Time	Researcher	Time Card, LCC, and Researcher's Log
Attempts	Calculate Performance	Researcher	Researcher Log
Successes	Calculate Performance	Researcher	Researcher's Log
<b>INDIVIDUAL SURVEY</b>			
Design Confidence	Analyze Process	Team	Ind. Post Questionnaire
Concept Design Satisfaction	Analyze Process	Team	Ind. Post Questionnaire
Detail Design Satisfaction	Analyze Process	Team	Ind. Post Questionnaire
Team Contribution Chance	Analyze Process	Team	Ind. Post Questionnaire
Team Contribution	Analyze Process	Team	Ind. Post Questionnaire
Team Interaction	Analyze Process	Team	Ind. Post Questionnaire
Agreement	Analyze Process	Team	Ind. Post Questionnaire
Team Leadership	Analyze Process	Team	Ind. Post Questionnaire
Outspokenness	Analyze Process	Team	Ind. Post Questionnaire
Team Familiarity	Analyze Process	Team	Ind. Post Questionnaire
AutoCAD Use	Analyze Process	Team	Ind. Post Questionnaire
Overall Satisfaction	Analyze Process	Team	Ind. Post Questionnaire
<b>TEAM SURVEY</b>			
Design Confidence	Analyze Process	Team	Team Post Questionnaire
Concept Design Satisfaction	Analyze Process	Team	Team Post Questionnaire
Detail Design Satisfaction	Analyze Process	Team	Team Post Questionnaire
Team Contribution Chance	Analyze Process	Team	Team Post Questionnaire
Team Contribution	Analyze Process	Team	Team Post Questionnaire
Team Interaction	Analyze Process	Team	Team Post Questionnaire
Agreement	Analyze Process	Team	Team Post Questionnaire
<b>SYMLOG DATA</b>			
Upward Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
Downward Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
U/D Net Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
Positive Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
Negative Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
P/N Net Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
Forward Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
Backward Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
F/N Net Score	Analyze Group Dynamics	Third Party	SYMLOG Rating Form
<b>OUTPUTS</b>			
Design Time	Calculate Design Performance	Researcher	Researcher's Log
Cube Size	Calculate Manuf. Performance	Researcher	Researcher's Log
Unique Parts	Calculate Support Performance	Researcher	Researcher's Log
Moving Parts	Calculate Support Performance	Researcher	Researcher's Log
Life-Cycle Cost	Calculate Support Performance	Researcher	Researcher's Log
Range Accuracy	Calculate System Performance	Researcher	Researcher's Log
Producability	Calculate System Performance	Researcher	Researcher's Log
Size	Calculate System Performance	Researcher	Researcher's Log

System Effectiveness	Calculate System Performance	Researcher	Researcher's Log
Cost Effectiveness	Calculate System Performance	Researcher	Researcher's Log
Process Time	Calculate Process Time	Researcher	Researcher's Log
Process Cost	Calculate Process Cost	Researcher	Researcher's Log
Elapsed Time	Analyze Process	Researcher	Researcher's Log

### 3.7.2. Calculation of Output Variables

#### 3.7.2.1. Design Performance

The goal of each team was to design and develop a system that would perform its intended function in a cost-effective manner (Blanchard and Fabrycky, 1990). Blanchard and Fabrycky defined cost-effectiveness as a first order parameter comprised of two second order parameters: life-cycle cost and system effectiveness. Figures of merit of each design were calculated by dividing system effectiveness by the life-cycle cost, as defined below. Cost effectiveness was the measure of design performance.

Table 3.3 shows the relationship between Blanchard and Fabrycky's generalized taxonomy and the data collected in this research:

Data Element	Applicable	How Calculated
I. Cost Effectiveness	Yes	System Effectiveness/Life-Cycle Cost
A. Life-Cycle Cost	Yes	Investment Cost + Operation and Support Cost
1. R&D Cost	No	
2. Investment Cost	Yes	Design Cost + Manufacturing Cost
a. Design Cost	Yes	<sup>1</sup>
b. Data Cost	No	
c. Test & Evaluation	Yes	Man-hours x \$60/hour
d. Manufacturing Cost	Yes	Man-hours x \$60/hour + Material Costs
e. Inventory Cost	No	
3. Operation & Support	Yes	Maintenance Cost
a. Maintenance Cost	Yes	<sup>2</sup>
4. Phase-Out Cost	No	
B. System Effectiveness	Yes	Performance
1. Performance	Yes	Range & Accuracy + Producability + Size
a. Range & Accuracy	Yes	<sup>3</sup>

<sup>1</sup> Design Cost = Conceptual Design Man-hours x \$60/hour + Detail Design Man-hours x \$60/hour + \$20 x number of team members for use of Groupware + \$50 for use of AutoCAD

<sup>2</sup> Maintenance Cost = \$5 x number of moving parts + 10% of material cost for spare parts

<sup>3</sup> Range & Accuracy = Points based on the following:

500 - Ball crossed finish line

400 - Ball crossed extended finish line

b. Reliability	No	
c. Maintainability	No	
d. Speed	No	
e. Transportability	No	
f. Producability	Yes	<sup>4</sup>
g. Size, Weight	Yes	<sup>5</sup>
2. Operational Availability	No	
3. Supportability	No	
4. Capacity	No	

**Table 3.3. Comparison with Blanchard and Fabrycky's Model**

A figure of merit for each design, cost effectiveness, was calculated for statistical comparison between treatments in the assessment of design performance.

*3.7.2.2. Determination of Process Time*

Process time was the summation of the individual task process times. The individual task process times were the time from the start of the task until its completion. Individual task times were recorded by each team on their Time Card and Exercise Log (Appendix D.11). The team then transcribed this data to the Life-Cycle Cost Form spreadsheet (Appendix D.5.1). The spreadsheet was programmed to calculate total process time.

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200 - Ball crossed hurdle line

0 - Ball did not cross hurdle line

<sup>4</sup> Producability = Points based on the following:

500 - Assembly Time < 5 minute

400 - Assembly Time < 10 minutes

300 - Assembly Time < 15 minutes

200 - Assembly Time < 20 minutes

100 - Assembly Time < 25 minutes

0 - Assembly Time > 25 minutes

<sup>5</sup> Size = Points based on the following:

500 - Size < 50 cubic inches

400 - 50 < Size < 100 cubic inches

300 - 100 < Size < 150 cubic inches

200 - 150 < Size < 200 cubic inches

100 - Size > 200 cubic inches

#### 3.7.2.3. *Determination of Process Cost*

The process cost is the sum of the labor cost and material cost. The labor cost is the product of the number of man-hours for each task times \$60 per hour. The number of the man-hours is the number of team members times the total process time. The material cost is \$50 for the use of AutoCAD plus \$20 times the number of team members for the use of groupware.

Process cost was an output variable of the Life-Cycle Cost Form spreadsheet.

#### 3.7.2.4. *Determination of Group Member Satisfaction*

Post-experiment questionnaires were completed by both individuals and teams. Specific questions measured this variable. Individual values were compared to responses that the team provided in order to determine a more accurate measurement of satisfaction.

#### 3.7.2.5. *Determination of Number of Ideas*

The number of ideas was collected automatically by those groups using groupware. The number of ideas generated by the manual nominal group technique was collected by the researcher. The level of discussion on ideas as measured by the number of comments during the discussion period was also collected in two ways. Groupware logged all comments on a log that permitted the number of comments to be counted by the researcher. In the manual condition, the researcher reviewed the videotape of several sessions and counted the number of substantive comments made.

#### 3.7.2.6. *Analysis of Group Dynamics*

The dynamics of the group was measured using the SYMLOG System. SYMLOG is an acronym for "A SYstem for the Multiple Level Observation of Groups." SYMLOG permits a single person to study a group in any setting, without the use of any special apparatus. SYMLOG constitutes a comprehensive and highly integrated system for the study of the behavior of individuals in groups.

The SYMLOG analysis of individual and group dynamics was performed after the conduct of each experiment. A third party, not the researcher, viewed the videotapes of each experiment and completed the SYMLOG Adjective Rating Form. The researcher then used this data to develop a directional profile of the group. The directional profile measured the group's tendency on three orthogonal axis: (1) Dominant vs. Submissive, (2) Friendly vs. Unfriendly, and (3) Instrumentally Controlled vs. Emotionally Expressive. These dimensions are labeled in physical models as: U - Upward, Dominant; D - Downward, Submissive; P - Positive, Friendly; N - Negative, Unfriendly; F - Forward, Instrumentally Controlled; B - Backward, Emotionally Expressive.

These quantitative measures permit correlation of group dynamics with quantifiable performance with respect to design performance, process cost, process time, and satisfaction.

### 3.7.3. Analysis Method for Research Questions

The following summarizes the questions asked in this research:

- *Research Question 1* asked how design performance is affected by engineering methodology, group size, or computer support.
- *Research Question 2* asked how process time is affected by engineering methodology, group size, or computer support.
- *Research Question 3* asked how process cost is affected by engineering methodology, group size, or computer support.
- *Research Question 4* asked how the satisfaction of group members toward the final design decision process is affected by engineering methodology, group size, or computer support.
- *Research Question 5* asked if there was a optimum combination of engineering methodology, group size, and computer support that created the greatest technological and personnel outcome.

This experiment was a three-factor experiment with two levels for each factor. The design is a completely randomized design and the analysis was a three-way analysis of variance (ANOVA) with five observations per cell for each of the dependent variables as discussed in Section 3.1.1.

## 4. Results

### 4.1. Overview of Experimental Process

Forty trials were conducted with 180 participants in the Macroergonomics and Group Decision Systems Laboratory at Virginia Tech. These trials were conducted from mid-November, 1996 to mid-February, 1997. All trials resulted in usable data. The following sections summarize the results of those trials.

### 4.2. Design Performance

Design Performance was an overall measure of whether the system achieved its performance specification, whether the design, manufacturing, and support organizations achieved their functional goals, and whether the system accomplished these things at the lowest life-cycle cost. Design performance was defined as cost effectiveness according to the Blanchard-Fabrycky model (1990). Cost effectiveness was calculated as system effectiveness divided by life-cycle cost. System effectiveness related several measures of performance (e.g., mission accomplishment) to a composite metric. This value was then divided by the calculated life-cycle cost of the system. Higher values of cost effectiveness relate to better design performance

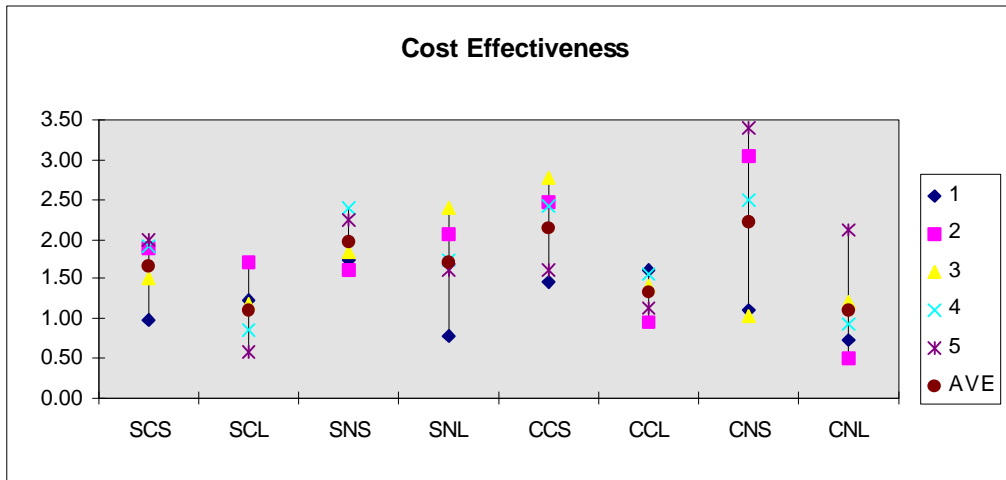
Table 4.1 shows the values of cost effectiveness as a function of condition. Conditions are labeled as follows:

- First Letter:           S (Sequential Engineering) or C (Concurrent Engineering)
- Second Letter:        C (Computer-Supported) or N (Non-Computer Supported)
- Third Letter:         S (Small Teams) or L (Large Teams)

<b>COST EFFECTIVENESS</b>									
<b>TRIAL</b>	<b>SCS</b>	<b>SCL</b>	<b>SNS</b>	<b>SNL</b>	<b>CCS</b>	<b>CCL</b>	<b>CNS</b>	<b>CNL</b>	<b>AVE</b>
<b>1</b>	0.99	1.24	1.75	0.77	1.45	1.61	1.10	0.74	1.21
<b>2</b>	1.88	1.72	1.60	2.06	2.48	0.95	3.05	0.50	1.78
<b>3</b>	1.52	1.18	1.85	2.38	2.76	1.42	1.03	1.21	1.67
<b>4</b>	1.91	0.85	2.39	1.73	2.42	1.55	2.50	0.92	1.78
<b>5</b>	1.99	0.59	2.25	1.60	1.61	1.13	3.40	2.11	1.84
<b>AVE</b>	1.66	1.12	1.97	1.71	2.14	1.33	2.22	1.10	1.65

**Table 4.1. Values of Cost Effectiveness by Condition**

The ranges for cost effectiveness are shown in Figure 4.1.



**Figure 4.1. Ranges for Cost Effectiveness by Condition**

*Research Question 1: How is design performance affected by engineering methodology, group size, and use of computer-supported cooperative work?*

#### 4.2.1. Engineering Methodology (EM)

There were two levels of the engineering methodology variable: sequential and concurrent engineering. The following hypotheses related to this variable:

- H<sub>0</sub>: Design performance will not be affected by engineering methodology.  
H<sub>1</sub>: The design performance of concurrent engineering groups will be greater than that of sequential groups ( $DP_{CE} > DP_{SE}$ ).

An ANOVA showed no significant difference between the effect of concurrent engineering and sequential engineering on design performance. The average means of those groups using concurrent engineering (mean = 1.6970) exceeded those groups using sequential engineering (mean = 1.6125).

#### 4.2.2. Group Size (GS)

There were two levels of the group size variable: small groups consisting of three people and large groups consisting of six people. The following hypotheses related to this variable:

- H<sub>0</sub>: Design performance will not be affected by group size.  
H<sub>1</sub>: The design performance of large groups will be greater than small groups ( $DP_{LG} > DP_{SG}$ ).

The design performance of small groups (mean = 1.9965) was significantly greater,  $F(1,32) = 13.14, p = 0.001$ , than that of large groups (mean = 1.3130) as shown in Table 4.2.

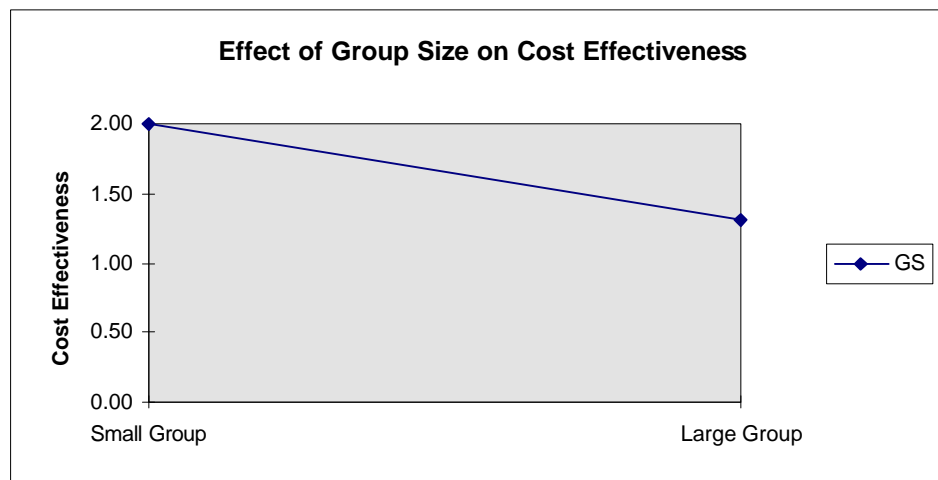


Source <sup>6</sup>	df <sup>7</sup>	SS <sup>8</sup>	MS <sup>9</sup>	F <sup>10</sup>	p <sup>11</sup>
EM	1	0.0714	0.0714	0.20	0.657
CSCW	1	0.3404	0.3404	0.96	0.335
GS	1	4.6717	4.6717	13.14*	0.001
EM*CSCW	1	0.7102	0.7102	2.00	0.167
EM*GS	1	0.7981	0.7981	2.24	0.144
CSCW*GS	1	0.0004	0.0004	0.00	0.973
EM*CSCW*GS	1	0.2176	0.2176	0.61	0.440
Error	32	11.3808	0.3557		
Total	39	18.1906			

\*  $p = .001$

**Table 4.2. Design Performance ANOVA Table**

Figure 4.2 shows the main effect of group size on cost effectiveness.



**Figure 4.2. Graph of Main Effect of Group Size on Cost Effectiveness**

<sup>6</sup> Source of variation

<sup>7</sup> Degrees of freedom

<sup>8</sup> Sum of squares

<sup>9</sup> Mean square

<sup>10</sup> F statistic

<sup>11</sup>  $p$  value

#### 4.2.3. Computer-Supported Cooperative Work (CSCW)

There were two levels of the computer-supported cooperative work variable: groups that used groupware in conceptual design and those that didn't. The following hypotheses related to this variable:

- H<sub>0</sub>: Design performance will not be affected by computer support.  
 H<sub>1</sub>: The design performance of computer-supported groups will be greater than non-computer-supported groups ( $DP_{CS} > DP_{NS}$ ).

An ANOVA showed no significant difference between the effect of using or not using groupware. The average means of those groups using groupware (mean = 1.5625) was less than those that did not use groupware (mean = 1.7470).

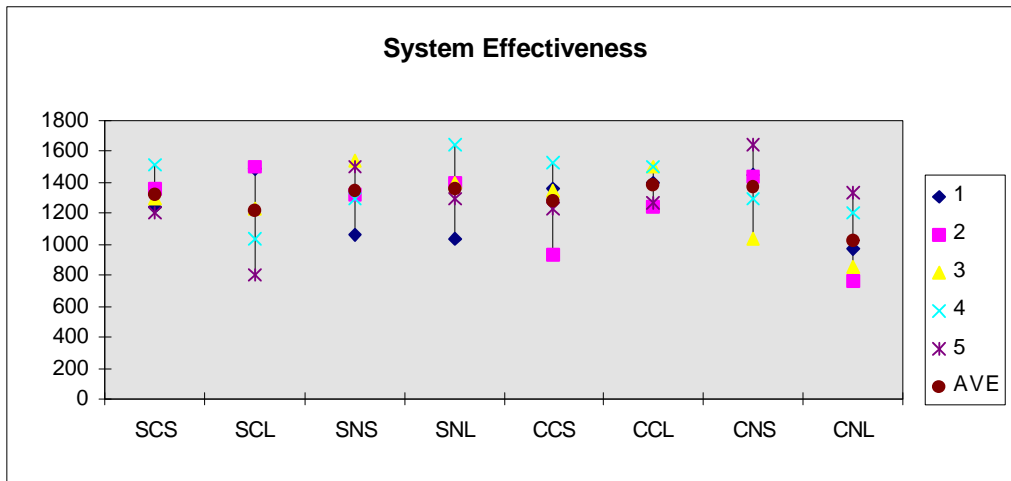
#### 4.2.4. System Effectiveness

Given that design performance is the ratio of system effectiveness and life-cycle cost, these variables were also analyzed. The values for system effectiveness are provided in Table 4.3.

SYSTEM EFFECTIVENESS									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	1240	1492	1066	1033	1366	1400	1446	972	1252
2	1361	1500	1317	1400	933	1248	1436	766	1245
3	1300	1233	1540	1400	1352	1500	1033	853	1276
4	1521	1033	1300	1650	1530	1500	1300	1200	1379
5	1200	800	1500	1300	1231	1266	1650	1333	1285
AVE	1324	1212	1345	1357	1282	1383	1373	1025	1288

**Table 4.3. Values for System Effectiveness by Condition**

The ranges for system effectiveness by condition are provided in Figure 4.3. There were no data values that were considered out of normal range.



**Figure 4.3. Ranges of System Effectiveness by Condition**

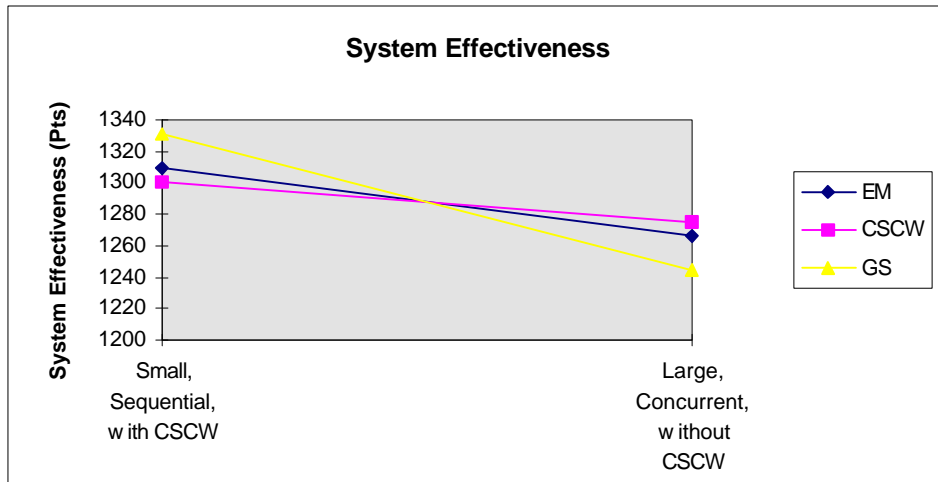
While there were no main effects for the variable with respect to system effectiveness, there was an interaction between engineering methodology, group size, and the use of computer-supported cooperative work,  $F(1,32) = 4.51, p = 0.041$ , as shown in Table 4.4.

Source	df	SS	MS	F	<i>p</i>
EM	1	18966	18966	0.42	0.523
CSCW	1	6528	6528	0.14	0.707
GS	1	75951	75951	1.67	0.206
EM*CSCW	1	116964	116964	2.57	0.119
EM*GS	1	13506	13506	0.30	0.590
CSCW*GS	1	65529	65529	1.44	0.239
EM*CSCW*GS	1	205492	205492	4.51*	0.041
Error	32	1456586	1456586		
Total	39	1959522			

\*  $p < 0.05$

**Table 4.4. System Effectiveness ANOVA Table**

The interaction of these variables is shown in Figure 4.4. The left of the chart represents the sequential, computer-supported, small group condition. The right of the chart represents the concurrent, non-computer-supported, large group condition.



**Figure 4.4. System Effectiveness Interaction Graph**

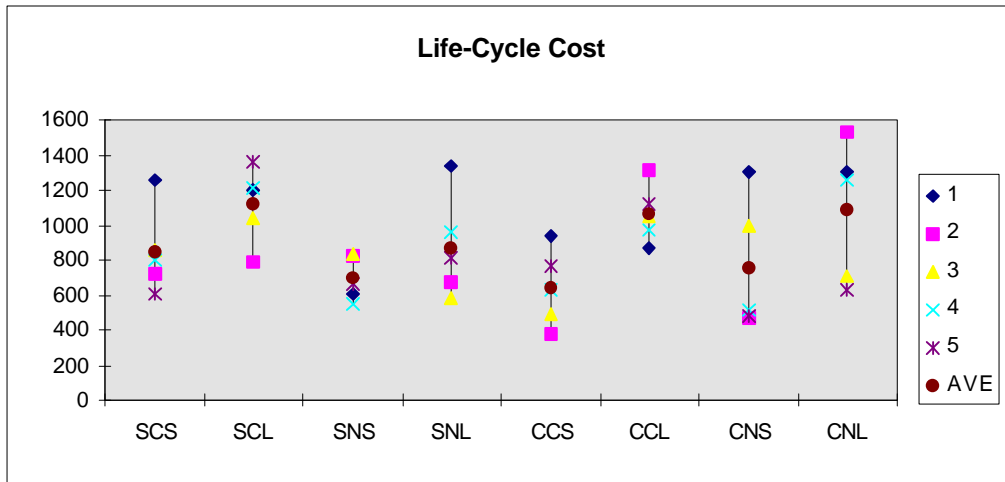
**4.2.5. Life-Cycle Cost**

The values for life-cycle cost by condition are shown in Table 4.5.

LIFE-CYCLE COST									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	1258	1202	606	1339	939	870	1307	1306	1103
2	722	788	820	679	376	1313	470	1529	837
3	853	1045	829	588	489	1055	996	703	820
4	798	1212	543	955	631	966	513	1258	860
5	604	1362	664	810	766	1116	484	632	805
AVE	847	1122	692	874	640	1064	754	1086	885

**Table 4.5. Values for Life-Cycle Cost by Condition**

The ranges for values of life-cycle cost are provided in Figure 4.5.



**Figure 4.5. Ranges for Life-Cycle Cost by Condition**

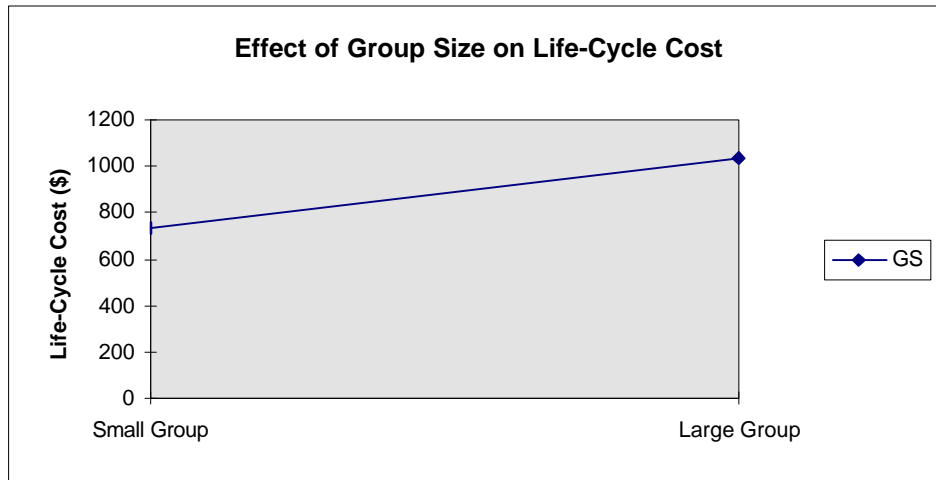
Group size was significant,  $F(1,32) = 12.44$ ,  $p = 0.001$ , as shown in Table 4.6.

Source	df	SS	MS	F	<i>p</i>
EM	1	44	44	0.00	0.981
CSCW	1	44489	44489	0.60	0.443
GS	1	918090	918090	12.44*	0.001
EM*CSCW	1	180634	180634	2.45	0.127
EM*GS	1	55801	55801	0.76	0.391
CSCW*GS	1	21437	21437	0.29	0.594
EM*CSCW*GS	1	0	0	0.00	0.998
Error	32	2360781	73774		
Total	39	3581275			

\*  $p = 0.001$

**Table 4.6. Life-Cycle Cost ANOVA Table**

The main effect of group size on life-cycle cost is shown in Figure 4.6.



**Figure 4.6. Main Effect of Group Size on Life-Cycle Cost**

**4.3. Process Time**

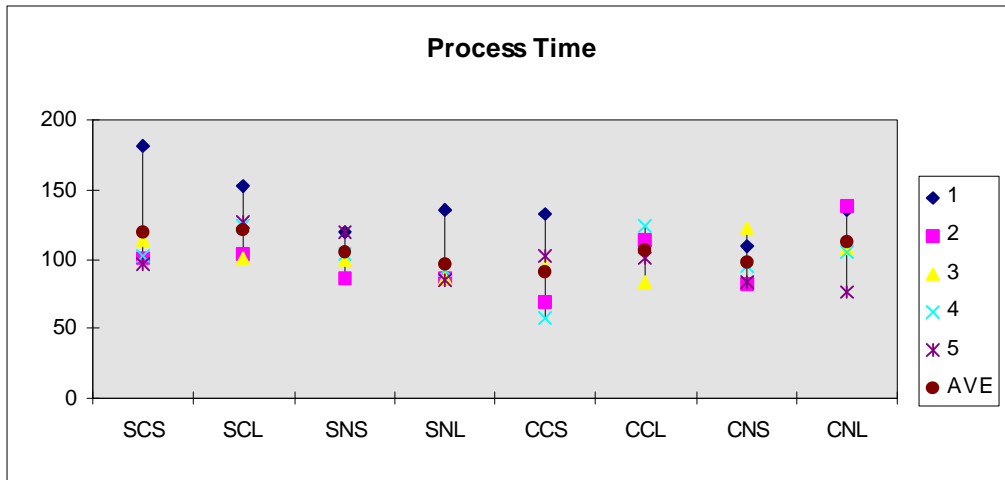
Process time was the time during a trial that the group was actually engaged in conceptual design, detail design, manufacturing, or testing. Training exercises, instructions, and design reviews (i.e., survey completion) were not included in process time.

The values for process time by condition are provided in Table 4.7.

PROCESS TIME									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	181	153	120	135	132	110	109	135	134
2	101	103	86	86	69	114	82	138	97
3	114	101	99	87	95	83	122	108	101
4	102	124	104	92	58	124	95	105	101
5	97	126	119	85	102	101	83	76	99
AVE	119	121	106	97	91	106	98	112	106

**Table 4.7. Values of Process Time by Condition**

The ranges of values of process time by condition are shown in Figure 4.7.



**Figure 4.7. Ranges of Process Time by Condition**

*Research Question 2: How is process time affected by engineering methodology, group size, and computer-supported cooperative work?*

#### 4.3.1. Engineering Methodology (EM)

The following hypotheses related to this variable:

- H<sub>0</sub>: Process time will not be affected by engineering methodology.  
H<sub>1</sub>: The process time of sequential engineering groups will be greater than concurrent engineering groups ( $PT_{SE} > PT_{CE}$ ).

There were no significant effects of engineering methodology on process time. The mean process time of sequential engineering groups (mean = 110.75 minutes) was greater than that of concurrent engineering groups (mean = 102.05 minutes).

#### 4.3.2. Group Size (GS)

The following hypotheses related to this variable:

- H<sub>0</sub>: Process time will not be affected by group size.  
H<sub>1</sub>: The process time of large groups will be greater than small groups ( $PT_{LG} > PT_{SG}$ ).

There were no significant effects of group size on process time. The mean process time of large groups (mean = 109.30 minutes) was greater than that of small groups (mean = 103.50 minutes).

#### 4.3.3. Computer-Supported Cooperative Work

The following hypotheses related to this variable:

H<sub>0</sub>: Process time will not be affected by computer support.

H<sub>1</sub>: The process time of computer-supported groups will be greater than non-computer-supported groups ( $PT_{CS} > PT_{NS}$ ).

There were no significant effects of computer-supported cooperative work on process time. The mean process time of computer-supported groups (mean = 109.50) was greater than that of non-computer-supported groups (mean = 103.30).

#### 4.4. Process Cost

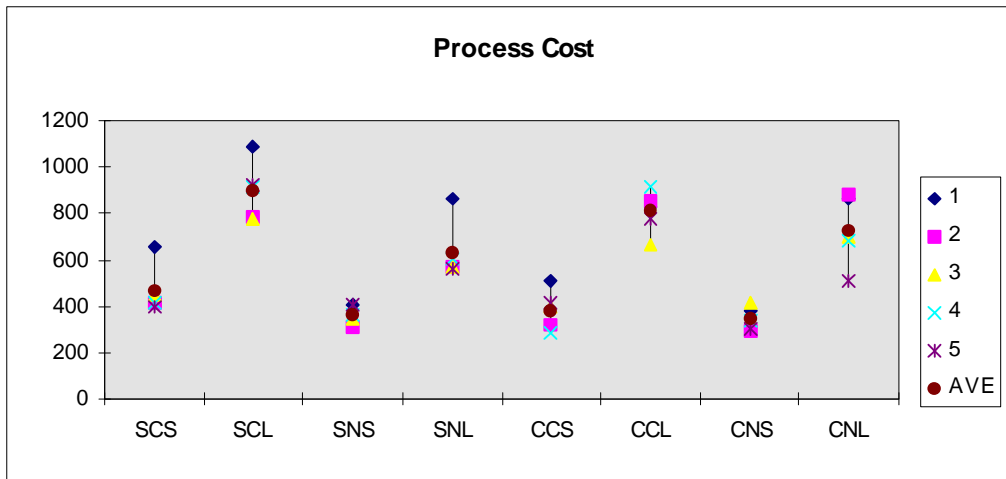
Process cost included the cost of labor, the cost of computer-supported cooperative work technology, and the cost of computer-aided design software (i.e., use of AutoCAD). Process cost was process time multiplied by the number of team members multiplied by their unit labor rate plus material costs. The values for process cost as a function of condition are shown in Table 4.8.

PROCESS COST									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	653	1088	410	860	506	830	377	860	698
2	413	788	308	566	317	854	296	878	553
3	452	776	347	572	395	668	416	698	541
4	416	914	362	602	284	914	335	680	563
5	401	926	407	560	416	776	299	506	536
AVE	467	898	367	632	384	808	345	724	578

**Table 4.8. Values of Process Cost by Condition**

Figure 4.8 provides the ranges of process cost by condition.





**Figure 4.8. Ranges of Process Cost by Condition**

*Research Question 3: Is process cost affected by engineering methodology, group size, or computer-supported cooperative work?*

#### 4.4.1. Engineering Methodology (EM)

The following hypotheses related to this variable:

H<sub>0</sub>: Process cost will not be affected by engineering methodology.

H<sub>1</sub>: The process cost of concurrent engineering will be less than sequential engineering ( $PC_{CE} < PC_{SE}$ ).

There were no significant differences between the process costs of groups using sequential or concurrent engineering. The mean process cost of concurrent engineering (mean = \$565.25) was less than the mean process cost of sequential engineering (mean = \$591.05).

#### 4.4.2. Group Size (GS)

The following hypotheses related to this variable:

H<sub>0</sub>: Process cost will not be affected by group size.

H<sub>1</sub>: The process cost of large groups will exceed that of small groups ( $PC_{LG} > PC_{SG}$ ).

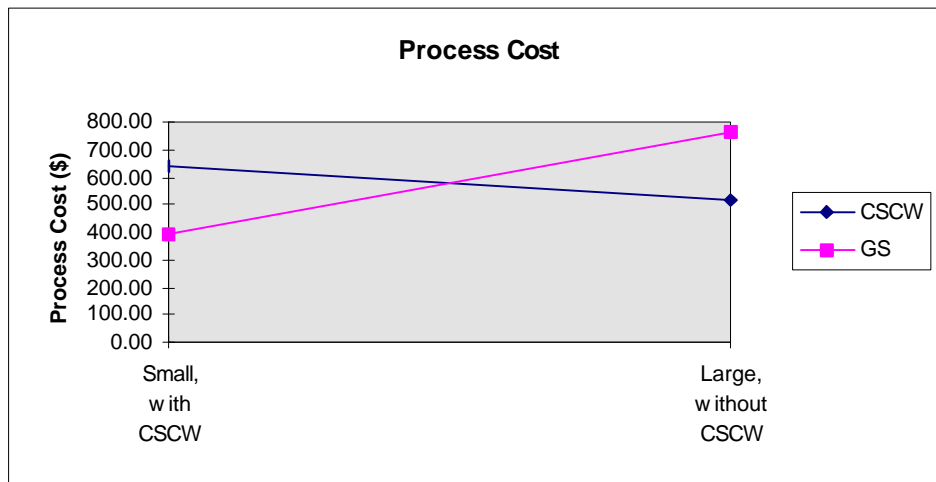
Large groups cost significantly more (mean = \$765.80) than small groups (mean = \$390.50),  $F(1,32) = 128.70$ ,  $p < 0.001$ , as shown in Table 4.9.

Source	df	SS	MS	F	p
EM	1	6656	6656	0.61	0.441
CSCW	1	149818	149818	13.69*	0.001
GS	1	1408501	1408501	128.70*	0.000
EM*CSCW	1	37088	37088	3.39	0.075
EM*GS	1	7290	7290	0.67	0.420
CSCW*GS	1	27878	27878	2.55	0.120
EM*CSCW*GS	1	9181	9181	0.84	0.367
Error	32	350201	10944		
Total	39	1996613			

\*  $p < 0.001$

**Table 4.9. Process Cost ANOVA Table**

The main effects of group size and computer support are shown in Figure 4.9.



**Figure 4.9. Group Size and Computer Support Effects on Process Cost**

#### 4.4.3. Computer-Supported Cooperative Work (CSCW)

The following hypotheses related to this variable:

- $H_0$ : Process cost will not be affected by computer support.  
 $H_1$ : The process cost of computer-supported groups will be greater than non-computer-supported groups ( $PC_{CS} > PC_{NS}$ ).

As shown in Table 4.9, the process cost of computer-supported groups (mean = \$639.35) significantly exceeded the cost of non-computer-supported groups (mean = \$516.95),  $F(1,32) = 13.69$ ,  $p = 0.001$ .

#### 4.5. Member Satisfaction

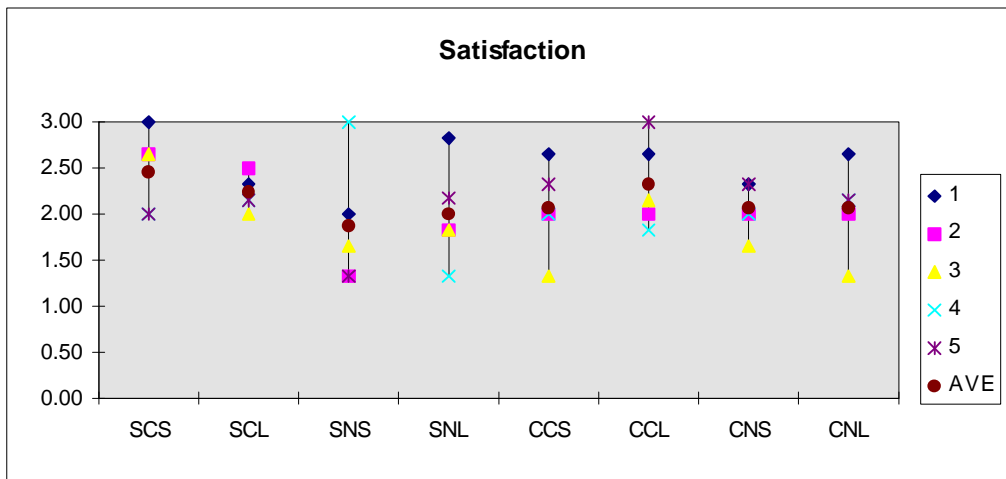
Member satisfaction was a subjective variable reported by the participants in a post-trial survey instrument. Participants responded to the question: “I was extremely satisfied with the process that was used to develop a concept, perform a detail design, manufacture, and test a system.” Responses were provided on a five point Likert scale with a value of one meaning strongly agree. Team values were calculated as the average of individual values.

The values for satisfaction by condition are shown in Table 4.10.

SATISFACTION									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	3.00	2.33	2.00	2.83	2.66	2.66	2.33	2.66	2.56
2	2.66	2.50	1.33	1.83	2.00	2.00	2.00	2.00	2.04
3	2.66	2.00	1.66	1.83	1.33	2.16	1.66	1.33	1.83
4	2.00	2.16	3.00	1.33	2.00	1.83	2.00	2.16	2.06
5	2.00	2.16	1.33	2.17	2.33	3.00	2.33	2.16	2.19
AVE	2.46	2.23	1.86	2.00	2.06	2.33	2.06	2.06	2.13

**Table 4.10. Values for Satisfaction by Condition**

The ranges of values for satisfaction by condition are provided in Figure 4.10.



**Figure 4.10. Ranges for Satisfaction by Condition**

*Research Question 4: Is the satisfaction of group members affected by engineering methodology, group size, or computer-supported cooperative work?*

#### 4.5.1. Engineering Methodology (EM)

The following hypotheses related to this variable:

H<sub>0</sub>: Group member satisfaction will be affected by engineering methodology.

H<sub>1</sub>: There will be no significant difference in member satisfaction in either concurrent or sequential engineering.

There was no significant difference in member satisfaction between concurrent and sequential engineering groups. The means for both concurrent engineering groups (mean = 2.1015) and sequential engineering group (mean = 2.1150) were approximately the same.

#### 4.5.2. Group Size (GS)

The following hypotheses related to this variable:

H<sub>0</sub>: Group member satisfaction will be affected by group size.

H<sub>1</sub>: There will be no significant difference in member satisfaction in either large or small groups.

There was no significant difference in member satisfaction between large and small groups. The mean for small groups was 2.0915 and the mean for large groups was 2.1250.

#### 4.5.3. Computer-Supported Cooperative Work (CSCW)

The following hypotheses related to this variable:

H<sub>0</sub>: Group member satisfaction will be affected by computer support.

H<sub>1</sub>: There will be no significant difference in member satisfaction.

There was no significant difference in member satisfaction between groups that used groupware in conceptual design and those that did not. The mean for groups that used groupware was 2.2465. The mean for groups that did not was 1.9700.

#### **4.6. Optimum Combination**

Of primary concern to practitioners is how these variables interact.

*Research Question 5: Is there an optimum combination of engineering methodology, group size, and computer support that creates the greatest technical and social outcome?*

The following hypotheses related to this variable:

H<sub>0</sub>: There is no optimum condition.

H<sub>1</sub>: Non-computer-supported, small, concurrent engineering groups will be the optimum condition.

No condition emerged as statistically significant.

#### **4.7. Summary**

The purpose of this chapter has been to present the results from analysis of quantifiable data. The chapter was organized by the overall research questions for this study which are summarized as:

What is the impact of engineering methodology, group size, and use of computer supported cooperative work on:

- Design Performance
- Process Time
- Process Cost
- Satisfaction

The results show that design performance of groups using concurrent or sequential engineering was not significantly different. Small groups significantly outperformed large groups. Groups that used computer-supported cooperative work did not outperform non-supported groups.

The results also demonstrated that engineering methodology, group size and the use of computer-supported cooperative work did not significantly affect process time.

The results also show that engineering methodology and the use of computer-supported cooperative work did not significantly affect process cost. However, the process cost of small groups was significantly less than large groups.

There were no significant differences in member satisfaction across all conditions.

## 5.0. Discussion

### 5.1. Overview

Managers of engineering design organizations must allocate scarce personnel and technological resources to the design process with the objective of maximizing its performance. This research considers three factors that represent resource allocation options that require management decision-making. Each of the factors: engineering methodology, group size, and computer-supported cooperative work technology have implications for: (1) the success of the system to be designed, (2) the time required to complete the design, (3) the cost of the design effort, and (4) the satisfaction of the personnel in the organization.

This research did not demonstrate any significant difference between groups that used concurrent engineering and groups that used sequential engineering. Therefore, the hypothesis that concurrent engineering would result in significantly greater design performance was not confirmed. The hypotheses that sequential engineering would require more time and cost more than concurrent engineering were also not confirmed. These results are shown to be invalid due primarily to the design of the experiment. A survey of industrial and academic experts in the design process unanimously agreed that concurrent engineering shortened product development times, increased product quality, lowered the cost of production, and lowered the life-cycle cost of a product.

This research demonstrated one effect of group size on performance. The hypothesis that larger groups would cost more was confirmed. Large groups performing this task were not able to overcome various processes losses. The hypothesis that larger groups would achieve greater design performance than small groups was not confirmed. Large groups had more ideas to work with but they were not able to execute those ideas any better than small groups. The hypothesis that larger groups would require more time was not confirmed. Large groups were able to employ division of labor strategies.

The hypotheses that computer-supported groups would take more time and cost more were confirmed. The hypothesis that groups that used computer-supported cooperative work would achieve greater design performance was not confirmed. This finding is counter to most of the literature on groupware that suggests that better decision quality will be an outcome.

Overall, the hypotheses that there would be no difference in satisfaction levels among all of the combinations of conditions was confirmed. Table 5.1 summarizes the findings of this research.

SUMMARY OF FINDINGS			
INDEPENDENT VARIABLE	ENGINEERING METHODOLOGY	GROUP SIZE	COMPUTER- SUPPORTED COOPERATIVE WORK
Design Performance	CE > SE Not Confirmed	L > S Not Confirmed	C > N Not Confirmed
Process Time	SE > CE Not Confirmed	L > S Not Confirmed	C > N Not Confirmed*
Process Cost	SE > CE Not Confirmed	L > S Confirmed	C > N Confirmed
Satisfaction	SE = CE Confirmed	L = S Confirmed	C = N Confirmed

\* This was confirmed when only considering conceptual design process time.

**Table 5.1. Overview of Research Results**

An unexpected outcome of this research related to the relative performance of teams composed of building construction students and teams composed of engineering students. Building construction teams significantly outperformed engineering teams. This research was able to discard team demographics as the causal factor. The group dynamics skills of the building construction students, developed reportedly through frequent team-based exercises in their classes, permitted them to reach consensus on numerous tasks faster than their engineering counterparts. This statistically insignificant incremental savings of time, integrated over the entire experiment, resulted in less cost and thus, greater system cost effectiveness.

Even though the population of participants used in this research was not homogeneous, some of the results are considered generalizable. The following sections discuss and interpret these results.

#### 5.1.1. Three-Way Interaction Effects

In order to increase the statistical power of the results of Chapter 4, an analysis of variance of the variables that had significant effects was performed eliminating three-way interactions.

Table 5.2 shows the ANOVA table for design performance. There was no change to the significance levels of main effects when eliminating the three-way interaction. Group size was significant,  $F(1,33) = 13.29, p = 0.001$ .

Source	df	SS	MS	F	<i>p</i>
EM	1	0.0714	0.0714	0.20	0.655
CSCW	1	0.3404	0.3404	0.97	0.332
GS	1	4.6717	4.6717	13.29*	0.001
EM*CSCW	1	0.7102	0.7102	2.02	0.165
EM*GS	1	0.7981	0.7981	2.27	0.141
CSCW*GS	1	0.0004	0.0004	0.00	0.973
Error	33	11.5984	0.3515		
Total	39	18.1906			

\*  $p = 0.001$

**Table 5.2. Design Performance ANOVA Table with Two-Way Interactions**

Table 5.3 shows the ANOVA table for life-cycle cost. There was no change to the significance levels of main effects when eliminating the three-way interaction. Group size was significant,  $F(1,33) = 12.83$ ,  $p = 0.001$ .

Source	df	SS	MS	F	<i>p</i>
EM	1	44	44	0.00	0.980
CSCW	1	44489	44489	0.62	0.436
GS	1	918090	918090	12.83*	0.001
EM*CSCW	1	180634	180634	2.52	0.122
EM*GS	1	55801	55801	0.78	0.384
CSCW*GS	1	21437	21437	0.30	0.588
Error	33	2360781	71539		
Total	39	3581275			

\*  $p = 0.001$

**Table 5.3. Life-Cycle Cost ANOVA Table with Two-Way Interactions**

Table 5.4 shows the ANOVA table for process cost. There was no change to the significance levels of main effects when eliminating the three-way interaction. Group size was significant,  $F(1,33) = 129.33$ ,  $p < 0.001$ , and computer-supported cooperative work was significant,  $F(1,33) = 13.76$ ,  $p = 0.001$



Source	df	SS	MS	F	<i>p</i>
EM	1	6656	6656	0.61	0.440
CSCW	1	149818	149818	13.76*	0.001
GS	1	1408501	1408501	129.33*	0.000
EM*CSCW	1	37088	37088	3.41	0.074
EM*GS	1	7290	7290	0.67	0.419
CSCW*GS	1	27878	27878	2.56	0.119
Error	33	350201	10890		
Total	39	1996613			

\*  $p < 0.001$

**Table 5.4. Process Cost ANOVA Table with Two-Way Interactions**

## 5.2. Engineering Methodology

The body of knowledge, albeit often anecdotal in nature, strongly suggested that concurrently engineering would result in superior design performance. Concurrent engineering groups (mean = 1.70) did not significantly outperform sequential engineering groups (mean = 1.61) in this experiment. Given that concurrent engineering has such strong face validity, it is necessary to examine whether this experiment adequately simulated the real world or whether the conclusion is valid.

### 5.2.1. Experimental Process

Sequential engineering was simulated in this experiment by serially giving functional goals to the members of each function (i.e., design, manufacturing, and support) in both conceptual design and detail design. In other words, the design function was given its goals at the onset of conceptual design and design deliberations commenced. The team discussed alternatives until they achieved consensus. Then manufacturing goals were given to the team. The team was again allowed to discuss alternatives and achieve consensus. Then support goals were given. The detail design process was similar. The goals for each function were different in conceptual and detail design.

Concurrent engineering was simulated by giving goals to all functions at the beginning of both conceptual and detail design. This process adequately simulated the ability of the downstream functions to influence the design in order to achieve their functional goals. However, there are two aspects of this experimental design that did not completely simulate a concurrent engineering process: (1) the experiment did not simulate concurrent downstream process design, and (2) teams had the ability to make radical changes in conceptual and detail design that would not have been possible in industrial settings.

Given LEGOs as manufacturing materials, there were no manufacturing processes to be designed. And, given that the nature of the task was to design a system for a single use, like a rocket, there were no support processes to be designed. Therefore, process design cost could not

be practically simulated. However, process design cost was not considered a performance factor. Therefore, this issue is not relevant.

In a sequential engineering process in industry, so many resources have been expended on a particular concept that changes proposed by the downstream functions must be minor rather than radical in nature. In this experiment, when teams were given their downstream goals, they could totally discard the current concept in favor of an entirely new one. This did happen, albeit infrequently. More often, the goals confirmed the concept the team already favored.

However, it could be argued that the simulation of sequential engineering was inadequate, thereby not demonstrating the superiority of concurrent engineering.

There are several other reasons why there were no significant effects of engineering methodology on cost effectiveness, process time, process cost, or satisfaction: (1) a team's design may have already met the functional goals of manufacturing and support, (2) the team did not think that achieving functional goals was as important as achieving the design goal, (3) individuals representing the functions may not have advocated their goals, and (4) detail design was abbreviated due to the level of CAD expertise of participants.

Before teams could consider the downstream functional goals in their designs, they had to be aware of the goals. Twenty-three teams (57.5%) openly shared (i.e., read to each other) their functional goals. Seventeen teams in the sequential engineering condition (85%) openly shared goals. Only 6 teams (15%) in the concurrent engineering condition openly shared goals. Whether the group used groupware, or whether it was large or small had little effect on goal sharing. Eleven teams (55%) that used groupware shared goals. Twelve teams (60%) that didn't use groupware shared goals. Twelve teams (60%) that were small shared goals, and eleven teams (55%) that were large shared goals.

One would expect that the concurrent engineering teams would share goals and the sequential teams might not. The process of distributing goals is believed to have created this anomaly. When goals were given out at the same time (i.e., concurrent engineering) to specific members of the functions, the team members perceived that they were a secret. When goals were given out serially (i.e., sequential engineering), team members wanted to see what their team members had received.

The decision to not tell teams to share goals was a conscious one to simulate reality. It also was designed to create conflict that had to be resolved. If every team member knew each function's goals, then the value of functional role-playing would have been lost. However, in retrospect, the experiment might have been more consistent if all teams had shared goals.

The following subsections elaborate on reasons why this experiment was not able to find significant differences between sequential and concurrent engineering.

#### *5.2.1.1. Design Already Met Functional Goals*

In many instances, the idea for a design in conceptual design, or the design that the team had created in detail design, met manufacturing and support goals. Therefore, few, if any, resources had to be expended to consider whether the design could be improved to meet the goal.

All teams knew that life-cycle cost was an important consideration. So many factored cost into their analyses from the beginning of the design process.

The data from conceptual design particularly confirm this point given that the mean for concurrent engineering (mean = 42 minutes) and sequential engineering (mean = 43 minutes) were nearly identical.

The experiment could have been designed to incorporate functional goals that were less likely to have been a natural outcome of the design process. For example, a possible support goal could have been that, in order to permit maintenance, you had to have access to all pieces.

#### 5.2.1.2. *Didn't Care About Functional Goals*

Some teams perceived that functional goals were not particularly important, even though they had been instructed that they were going to be individually evaluated on the accomplishment of functional goals. A typical attitude that was observed was that if the system worked, that was all that was important.

Another reason for the lack of advocacy of functional goals was time. Teams were sensitive to the cost of time and realized that further debate on design issues had a cost associated with it. Some teams chose to proceed on, recognizing that they would not achieve their functional goals but the system would be more cost effective. This situation is frequently encountered in industry, particularly with respect to support goals.

#### 5.2.1.3. *Didn't Advocate Functional Goals*

In some cases, the demographics of the team played an important part in functional goal achievement. On those teams in which international students were members in downstream functional roles, there was often little advocacy of functional goals. Strong personalities in these positions had the opposite effect.

One measure of advocacy is conflict. If teams felt like there was little team conflict, it might have been because of manufacturing and support functional passivity with respect to goal advocating. An analysis of conflict was performed based on the results of a survey at the conclusion of the experiment (IPEQ#5). Participants were given the statement, "There was little discussion conflict on our team." The results shows little difference in conflict between teams using concurrent engineering (mean = 1.65) and sequential engineering (mean = 1.72).

During the Preliminary Design Review, participants were asked to respond to the following statement (PDR#4), "Each functional member achieved his or her functional goals." The response to this statement (mean = 2.208, standard deviation = 0.463) showed that most teams were in the "agree" to "undecided" range.

There was much stronger opinion by participants that they had achieved their functional objectives at the conclusion of detail design (FDR#4) (mean = 1.663, standard deviation = 0.463). Participants were also asked whether the design, manufacturing and support organizations had influenced the detail design process. The support function (FDR#5) (mean = 1.87, standard deviation = 0.637) had less influence than design (FDR#7) (mean = 1.853, standard deviation =

0.453) or manufacturing (FDR#6) (mean = 1.778, standard deviation = 0.510). The inability of the support function to influence the design process occurs frequently in industry.

#### *5.2.1.4. Abbreviation of Detail Design*

In an industry implementation of sequential engineering, drawings would be issued prior to evaluation of the drawings by manufacturing and support personnel. Evaluation would necessarily result in change orders or engineering change proposals that would cause drawings to be revised and reissued. In this experiment drawings were only created once. This was a conscious decision to limit the total experiment time. Each drawing required at least twenty-five minutes to prepare. The concern was that if too much effort was expended on drawing production, the outcome could depend more on a team's CAD expertise than on the various process variables. While everyone's CAD expertise was sufficient to complete the task, if drawings had to be released several times, the process time, and therefore, cost effectiveness, would have been very correlated to either CAD expertise or the complexity of the drawings for a particular type of system. If drawings had to be created several times to meet the goals of the manufacturing and support organizations, the process time would have been substantially longer for sequential engineering. The result would probably have been that the difference between sequential and concurrent engineering would have been significant.

#### *5.2.1.5. Summary*

For the above reasons, it is believed that this experiment did not adequately simulate sequential and concurrent engineering. Now that a database of feasible solutions and their corresponding times and costs has been created, it would be possible to examine this issue more accurately by conducting experiments on specific phases of the design process.

### 5.2.2. Experimental Results Related to Engineering Methodology

It was hypothesized that the design performance of concurrent engineering groups would be greater than sequential engineering groups. It was expected that concurrent engineering groups would require less time and, hence, less cost than sequential groups. The process time of concurrent engineering groups (mean = 102 minutes) was not significantly less than that of sequential engineering groups (mean = 111 minutes). Since the times were not significant, neither were the costs. Concurrent engineering groups (mean = \$565) were not significantly less costly than sequential engineering groups (mean = \$591).

As hypothesized, there was no difference in satisfaction between teams that used concurrent engineering (mean = 2.13) and teams that used sequential engineering (mean = 2.14).

### 5.2.3. External Survey Results Related to Engineering Methodology

The purpose of the external survey was to add more external validity to the research results. Experts from industry and academia were surveyed to determine their opinion of the value of concurrent engineering as compared to sequential engineering. Twenty-seven surveys

were sent out. There were ten responses and two returned for incorrect addresses. The average number of years of experience in engineering design of the ten respondents was twenty-two years, ranging from a high of forty-four to a low of five. The experts were asked to respond to six statements about concurrent engineering using a five-point Likert scale with one equaling “strongly agree.” The results of the survey are provided in tabular and graphical form in Appendix F.4.

All respondents thought that concurrent engineering shortened product development times (mean = 1.2, standard deviation = 0.422). They also thought that concurrent engineering increased product quality (mean = 1.4, standard deviation = 0.516), lowered the cost of production (mean = 1.5, standard deviation = 0.527), and lowered the life-cycle cost of a product (mean = 1.3, standard deviation = 0.483).

All but one respondent thought that the use of multidisciplinary or cross-functional teams was the major tenet of concurrent engineering (mean = 1.7, standard deviation = 1.252). Lake (1997) stated, “One of the biggest problems with concurrent engineering is that it has been equated to teams. Teams are powerful and should be used but they must be structured right (e.g., to product structure). As important are the processes, methods, and tools (not necessarily automated).”

Respondents generally thought that groups using concurrent engineering were more likely to be satisfied than sequential engineering groups (mean = 1.8, standard deviation = 0.632), however, one respondent thought that it largely depended on the company climate and an individual’s feeling about teams and teamwork. Slalak (1997) stated that, “Some people dislike working in teams, so team selection is critical to the success of concurrent engineering.”

#### 5.2.4. Summary

While the experiment may not have shown that the difference between concurrent and sequential engineering was significant, it did in many respects replicate some aspects of real organizations. Design organizations often fail to consider downstream process issues due to: (1) the pressure to release drawings, (2) downstream representative’s failures to assert their requirements, or (3) downstream representative’s lack of power to cause their requirements to be considered.

Implementing a concurrent engineering process is no guarantee that the expected benefits of this process are being achieved. Real organizations that profess to use concurrent engineering may not be achieving the expected results if the downstream members of the teams are not able to or do not exert influence on the design.

### **5.3. Group Size**

The literature is very mixed on the impact of group size on any performance task. There is very little information on engineering group performance as a function of group size. The effect of size on group performance is the result of two opposing forces. Added resources in larger groups contribute to the number of alternatives for the group to decide among. Therefore, the system effectiveness of a group, the numerator of cost effectiveness, should have been greater in

large groups. These same added resources may make it more difficult to achieve consensus resulting in a decrease of the effectiveness of the group. This would manifest itself in an increase in process time and therefore, life-cycle cost, the denominator of cost effectiveness.

Steiner's theory of group productivity states that group productivity depends upon three classes of variables: task demands, resources, and process (Steiner, 1972). According to Steiner, group performance should increase with group size when the task is either additive (i.e., the outcome is the result of some combination of individual products), or disjunctive (i.e., the outcome depends upon at least one person in the group performing the task). This experiment was designed to be an additive task. Unique information was given to a subset of the team that should have been integrated by the team into a final decision. Hence, the expectation was the system effectiveness would increase as a function of group size.

This research showed that group size did have a significant affect on cost effectiveness. Cost effectiveness is defined as system effectiveness divided by life-cycle cost. In order to determine why group size had a significant affect on cost effectiveness, the following sections consider the effect on system effectiveness and life-cycle cost.

#### 5.3.1. System Effectiveness

System effectiveness was determined by four variables: system mission performance, system producability, the manufactured size of the system, and the robustness of the system. The literature consistently suggests that the selection of the concept for the system "locks-in" many of these parameters.

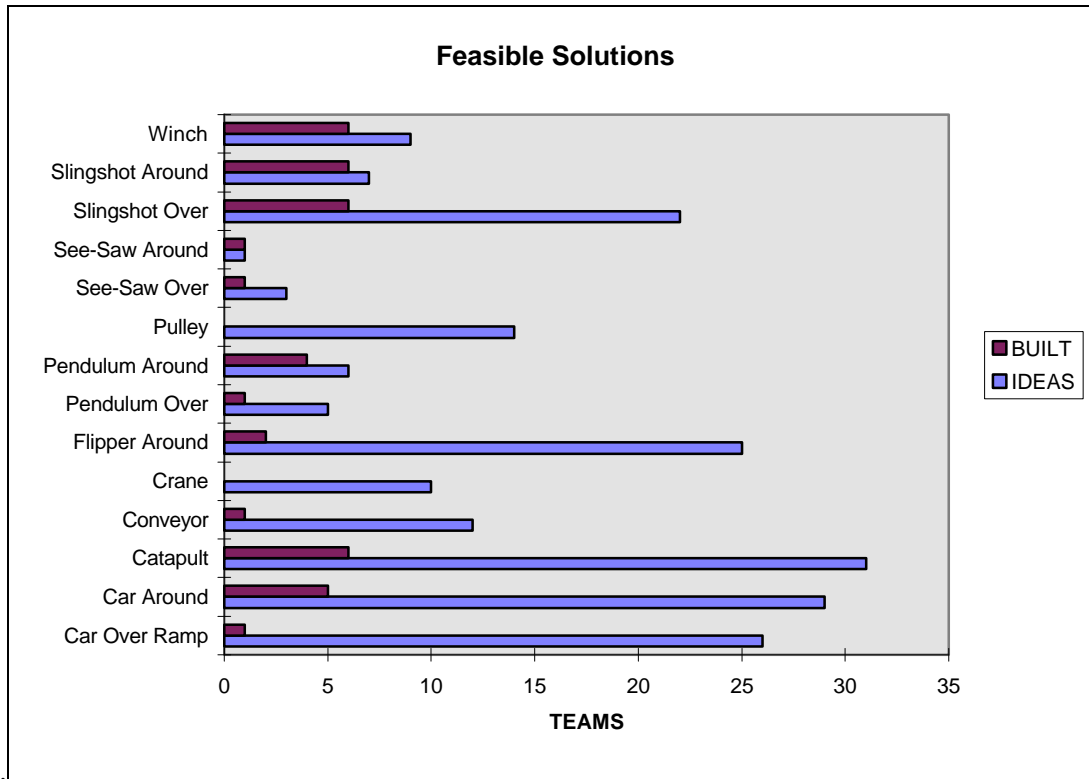
In conceptual design, it was expected that larger groups would be able to create more concepts than smaller groups. More concepts, with appropriate consideration of goals of producability, reducing the manufactured size of the system, and robustness should lead to a better choice of a conceptual approach to the solution of the problem.

In detail design, it was expected that larger groups would have more resources and more expertise to apply to problems in detail design. Large teams would hopefully translate their resources into better execution of the design concept.

Teams were told that they could change their concept in detailed design if it turned out to not be feasible. Only one team was not able to execute the design concept they had conceived in conceptual design. The team had other, more feasible ideas, but a dominant leader of the group, an engineering group, insisted on pursuing his idea. When the team finally abandoned the leader's idea, after the loss of about an hour, they were able to complete the trial successfully.

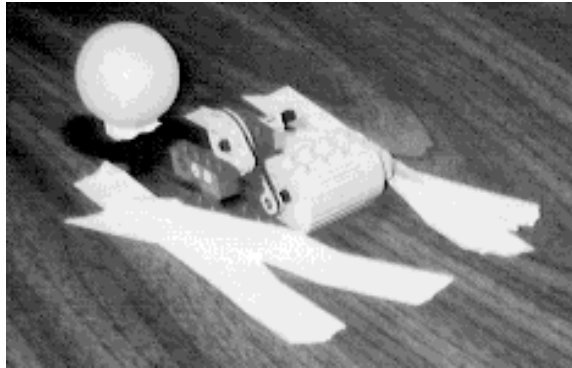
Fourteen different ideas comprised the feasible solution set. Feasible ideas were ideas that had either been built by a team or previously demonstrated by the researcher to be a design that could be built. These ideas can be categorized in the following conceptual manners: whether their strategy was to go over or around the hurdle, whether they used stored energy or motor energy to initiate ball movement, whether the plane of motion was horizontal or vertical, whether the motion was rotational or linear. Had a team been able to derive these conceptual categories, they would have been able to derive the entire solution set. Twelve of the fourteen feasible ideas were actually constructed by teams.

Figure 5.1 shows a list of the feasible solution set with the number of teams that conceived each idea, and the number of teams that constructed that idea. As can be seen from the chart, a catapult was conceived by over 75% of the teams. However, only six teams built catapults. Slingshots around the hurdle, slingshots over the hurdle, and winches were each built by six teams. The solution set contained many feasible solutions.

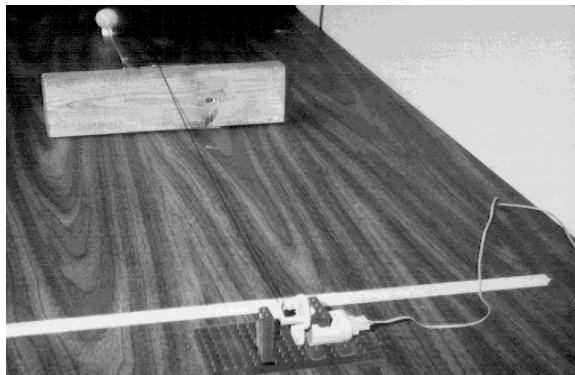


**Figure 5.1. Feasible Solution Chart**

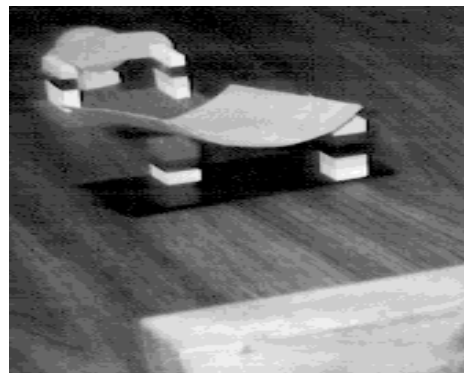
Figures 5.2, 5.3, and 5.4 show examples of the systems that were designed and built the most frequently.



**Figure 5.2. Typical Catapult Design**



**Figure 5.3. Typical Winch Design**



**Figure 5.4. Typical Slingshot Design**



Table 5.5 shows the number of feasible ideas that were developed by condition. This chart shows that the average number of ideas per team did not increase as the number of trials increased. This is encouraging because it shows that teams did not share their ideas with others that had not yet participated in the experiment. Teams were instructed at two points in the experiment to not share results with others because they would lose their competitive edge. Only two teams thought of as many as nine of the fourteen feasible ideas.

TOTAL FEASIBLE IDEAS									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	4	3	4	6	2	7	6	4	4.50
2	4	7	3	5	6	6	3	7	5.13
3	3	5	4	6	5	9	5	6	5.38
4	4	6	2	7	4	5	4	5	4.63
5	4	4	4	5	7	9	5	5	5.38
AVE	3.80	5.00	3.40	5.80	4.80	7.20	4.60	5.40	5.00

**Table 5.5. Feasible Ideas by Condition**

The results of an ANOVA on this data show that group size,  $F(1,32) = 16.88, p < 0.001$  and engineering methodology,  $F(1,32) = 5.84, p = 0.022$ , both have significance, as shown in Table 5.6.

Source	df	SS	MS	F	<i>p</i>
EM	1	10.000	10.000	5.84*	0.022
CSCW	1	1.600	1.600	0.93	0.341
GS	1	28.900	28.900	16.88**	0.000
EM*CSCW	1	3.600	3.600	2.10	0.157
EM*GS	1	0.100	0.100	0.06	0.811
CSCW*GS	1	0.100	0.100	0.06	0.811
EM*CSCW*GS	1	4.900	4.900	2.86	0.100
Error	32	54.800	1.712		
Total	39	104.000			

\*  $p < 0.05$

\*\* $p < 0.001$

**Table 5.6. Feasible Idea ANOVA Table with Three-Way Interaction**

Large groups (mean = 5.85) had more concepts to work with than small groups (mean = 4.15). An ANOVA was recalculated eliminating the three-way interaction. There were no changes to significant levels of main effects when eliminating the three-way interaction. The

results of this ANOVA, shown in Table 5.7, show that group size,  $F(1,33) = 15.97$ ,  $p < 0.001$  and engineering methodology,  $F(1,33) = 5.53$ ,  $p = 0.025$ , have significance.

Source	df	SS	MS	F	p
EM	1	10.000	10.000	5.53*	0.025
CSCW	1	1.600	1.600	0.88	0.354
GS	1	28.900	28.900	15.97**	0.000
EM*CSCW	1	3.600	3.600	1.99	0.168
EM*GS	1	0.100	0.100	0.06	0.816
CSCW*GS	1	0.100	0.100	0.06	0.816
Error	33	59.700	1.809		
Total	39	104.000			

\*  $p < 0.05$

\*\* $p < 0.001$

**Table 5.7. Feasible Idea ANOVA Table with Two-Way Interactions**

There is no experimental explanation for why those groups using sequential engineering (mean = 4.5) would not have had approximately the same number of feasible ideas as groups doing concurrent engineering (mean = 5.5). Large concurrent engineering groups using groupware created the most ideas.

Since system effectiveness consisted of four unrelated factors (i.e., performance, producability, manufactured size, and robustness) an arbitrary scoring system was developed that allocated a maximum of 500 points to each factor except robustness. This process therefore assumed that each of the first three factors was equal in importance. The distribution of points within a factor was also arbitrary and based on a normal distribution of performance for each factor during pilot testing of the experiment.

The concept of robustness was introduced into the experiment in order to simulate reality and make the problem more creatively challenging. Since robustness was a design functional goal, many teams considered it, especially during conceptual design. Designs that were able to meet the performance specification with the substitution of a golf ball for a ping-pong ball were given a 10% bonus in system effectiveness. The value of 10% was suggested by Professor Ben Blanchard in consideration of the Blanchard/Fabrycky model of cost effectiveness that was used herein.

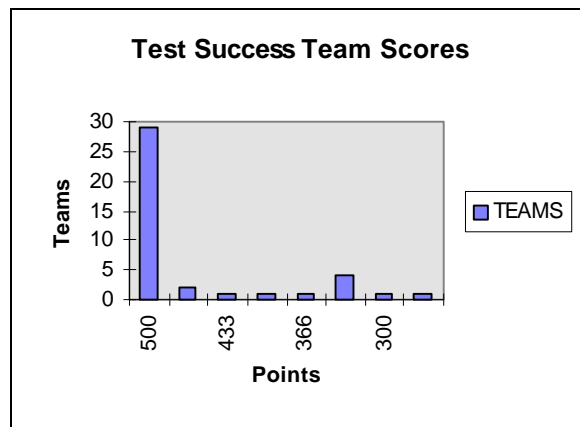
The following subsections present the results related to the component factors of system effectiveness.

#### 5.3.1.1. System Performance

Given the number of possible solutions, were groups able to achieve the system specification (i.e., solve the problem) equally well with the various alternative solutions? Twenty-

nine teams met the performance specification in each of three trial runs. Six teams were successful in two attempts. Four teams were successful in one attempt and one team was not successful in any attempts. Even the team that was unsuccessful moved the ping-pong ball across the extended finish line.

The scoring system used for measuring whether the system met its performance specification was: 500 points for crossing the finish line as required, 400 points for crossing the extended finish line, and 200 points for crossing the hurdle. As shown in Figure 5.5, based on three trials, 29 teams scored 500 points, the maximum score possible.

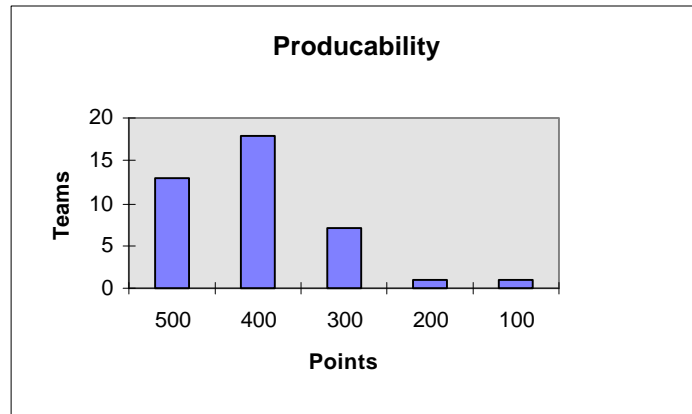


**Figure 5.5. Distribution of Team Scores for Successful Tests**

An ANOVA was performed on this data to determine if group size had significance with respect to the degree of success of a system. It did not. The mean score for large groups was 448 and for small groups it was 473. Therefore, the system chosen by each team did not significantly impact the performance factor of overall system effectiveness which was part of the numerator of the cost effectiveness measure of design performance.

### 5.3.1.2. *Producability*

Producability was measured as the amount of time required to manufacture the system. The maximum score of 500 points was awarded to systems that could be built within 5 minutes, 400 points for systems that could be built within 10 minutes, 300 for systems that could be built within 15 minutes, 200 for systems that could be built within 20 minutes, 100 for systems that could be built within 25 minutes, and no points for systems that took longer than 25 minutes to build. Figure 5.6 shows the number of teams that scored each point value.



**Figure 5.6. Distribution of Team Scores for Producability**

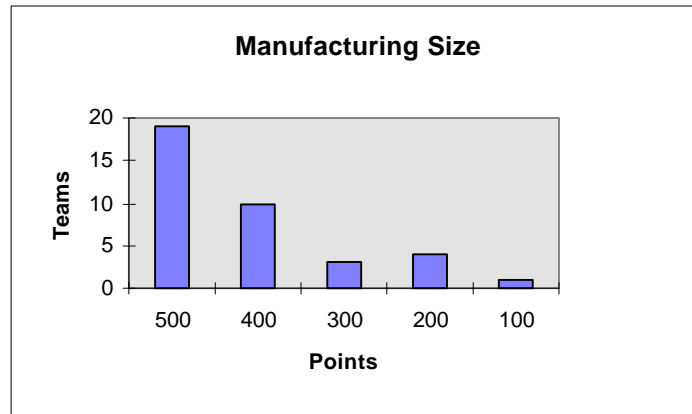
An ANOVA was performed on the producability scores. There was no significance between large groups (mean = 405) and small groups (mean = 400). It would have been expected that large groups could have more likely conceived more producable design.

#### 5.3.1.3. *Manufacturing Size*

The manufacturing size of the system was defined as the smallest cube that all of the subsystems could be nested into. Subsystems were defined as non-contiguous parts. For example, a slingshot that hit the ball off of a side wall would have consisted of two subsystems. Minimizing the manufacturing size was a functional goal of the manufacturing organization in detail design.

The maximum score awarded was 500 points for systems with a volume of less than 50 cubic inches, 400 for less than 100 cubic inches, 300 for less than 150 cubic inches, 200 for less than 200 cubic inches, and 100 for greater than 200 cubic inches. Figure 5.7 shows the distribution of scores based on manufacturing size.

An ANOVA was performed on manufacturing size scores. There was no significant difference between large groups (mean = 370) and small groups (mean = 415). It would have been expected that large groups would have been able to apply their resources to achieving more compact systems.



**Figure 5.7. Distribution of Team Scores for Manufacturing Size**

5.3.1.4. *Robustness*

Systems that did not completely succeed (i.e., three successful trials in three attempts) during normal testing were not tested for robustness. Robustness trials were conducted with the same scoring system as normal trials. Teams were awarded a percentage of the maximum possible 10% in proportion to their success.

Table 5.8 shows the bonus system effectiveness points that were awarded to each team by condition. The maximum award possible was 150 points. Note that teams in every condition and every trial scored robustness points. Interestingly, the large concurrent engineering groups that conceived the most ideas, achieved the lowest robustness scores.

ROBUSTNESS POINTS									
TRIAL	SCS	SCL	SNS	SNL	CCS	CCL	CNS	CNL	AVE
1	40	92	0	0	0	0	46	72	31.25
2	61	0	17	0	0	48	36	0	20.25
3	0	0	140	0	52	0	33	53	34.75
4	121	0	0	150	130	0	0	0	50.13
5	0	0	0	0	31	0	150	0	22.63
AVE	44.40	18.40	31.40	30.00	42.60	9.60	53.00	25.00	31.80

**Table 5.8. Robustness Values by Condition**

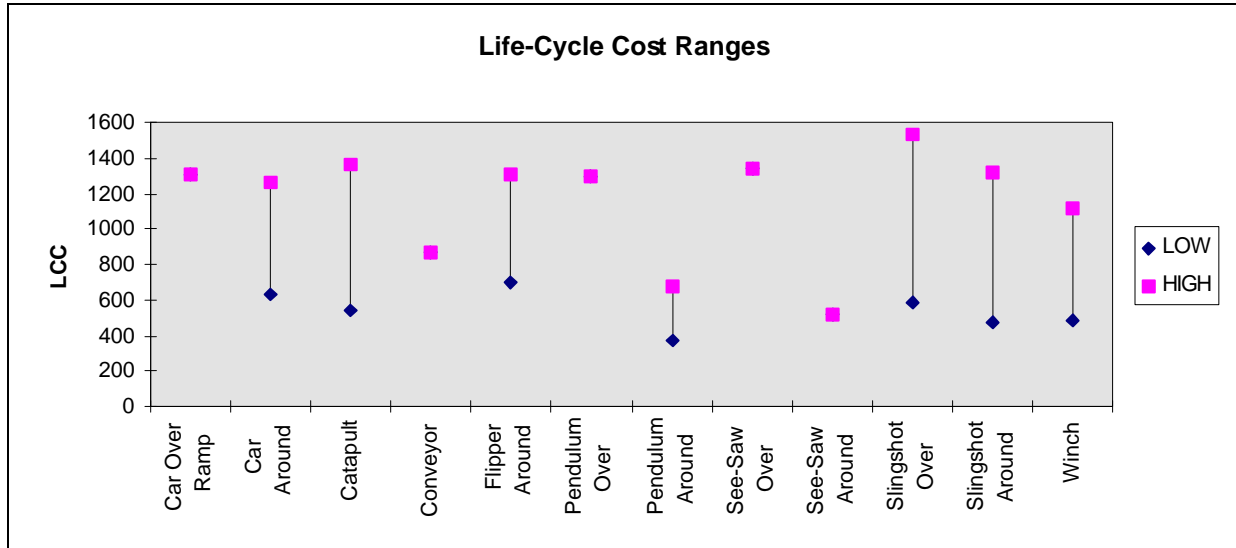
An ANOVA was performed on the robustness data and there were no significant main effects or interactions. In addition, a correlation was performed between robustness and cost effectiveness. This showed no correlation (correlation = 0.249).

In summary, large teams created more concepts to work with but the additional ideas were not translated into designs that had higher system effectiveness scores.

### 5.3.2. Life-Cycle Cost

As shown in Chapter 4, group size was a significant factor in cost effectiveness. It has been shown that for system effectiveness, the numerator of cost effectiveness, group size did not have significance. Therefore, life-cycle cost, the denominator of cost effectiveness, will now be examined. Life-cycle cost consisted of a labor and a material component. The labor component directly correlated to group size since all members of the team charged the same labor rate (\$1 per minute), irrespective of functional role on the team. The material component corresponds to the choice of idea and its execution.

Did the system chosen have implications for life-cycle cost? Figure 5.8 shows that the range of costs for each possible solution, except for those in which only one solution was built, is large. This means that, in most cases, the execution of the idea rather than the idea itself related to life-cycle cost. Since life-cycle cost is based on labor time and material, it cannot be argued that a particular idea took longer to build or required more material than another.



**Figure 5.8. Ranges of Life-Cycle Costs for each Solution**

The following subsections take a closer look at the labor and material components of the systems that were built.

#### 5.3.2.1. Labor

An ANOVA on the direct labor costs was conducted. Group size was significant,  $F(1,32) = 108.95, p < 0.001$ , as shown in Table 5.9.

Source	df	SS	MS	F	<i>p</i>
EM	1	6656	6656	0.61	0.441
CSCW	1	10498	10498	0.96	0.335
GS	1	1192321	1192321	108.95*	0.000
EM*CSCW	1	37088	37088	3.39	0.075
EM*GS	1	7290	7290	0.67	0.420
CSCW*GS	1	5198	5198	0.48	0.496
EM*CSCW*GS	1	9181	9181	0.84	0.367
Error	32	350201	10944		
Total	39	1618433			

\*  $p < 0.001$

**Table 5.9. Direct Labor ANOVA Table with Three-Way Interaction**

The ANOVA was recalculated eliminating the three-way interaction. There was no change to the significance level of group size when the interaction was eliminated,  $F(1,33) = 109.48$ ,  $p < 0.001$ , as shown in Table 5.10.

Source	df	SS	MS	F	<i>p</i>
EM	1	6656	6656	0.61	0.440
CSCW	1	10498	10498	0.96	0.333
GS	1	1192321	1192321	109.48*	0.000
EM*CSCW	1	37088	37088	3.41	0.074
EM*GS	1	7290	7290	0.67	0.419
CSCW*GS	1	5198	5198	0.48	0.494
Error	33	359382	10890		
Total	39	1618433			

\*  $p < 0.001$

**Table 5.10. Direct Labor ANOVA Table with Two-Way Interactions**

The means for large groups (mean = 655) were more than twice the means for small groups (mean = 310). This implies that there were more process losses for larger teams. An analysis of the post experiment questionnaires (IPEQ#6) showed that there was more conflict among larger groups (mean = 1.76) than smaller groups (mean = 1.61). This conflict may have contributed to increased process time and more process losses.

#### 5.3.2.2. *Material*

Given that there were more people seeking to minimize the material used there might have been an effect of group size on material cost. An ANOVA of material costs showed no significant main effects or interactions. The cost of material for large groups (mean = \$243) was less than the mean cost for small groups (mean = \$302). The cost of material would have had to have been significantly less in large groups to offset the direct labor cost for life-cycle cost to not be significant. It was not.

#### 5.3.3. Process Time

As shown in Chapter 4, there were no significant effects of group size on process time. Large groups took longer (mean = 109.3 minutes) than small groups (mean = 103.5 minutes) but it was not significant. It was thought that possibly process time would have been significant had not the previously mentioned small group taken an additional hour. However, substitution of a mean value for that group's process time, did not cause the ANOVA to show that group size was significant.

Large groups were generally not able to attack the problem by division of labor. They might have been able to, except in the absence of a leader, teams typically did not organize themselves so they could tackle separate tasks. In other words, everybody worked on every problem, especially in detail design when the work was partitionable.

#### 5.3.4. Process Cost

Process cost was equal to direct labor cost (process time multiplied by the labor rate of \$1 per minute) plus the cost of groupware, when applicable, and the use of CAD. The cost of groupware was \$20 per team member. The cost of CAD was the same for all teams and was \$50. As shown in Chapter 4, group size had a significant effect on process cost. Process time was independent of the number of team members. Process cost was a direct function of the number of team members. So since direct labor cost was shown to have a significant effect by group size, it follows that process cost would also.

#### 5.3.5. Satisfaction

The difference in satisfaction between large groups (mean = 2.1250) and small groups (mean = 2.0915) was insignificant. Small groups indicated to the researcher that they thought that large groups would be unsatisfied. They believed that there would be too many people in the way to efficiently solve the task. However, large groups did not seem to be at all dissatisfied with the process. There was some dissatisfaction expressed by large groups about the small size of the laboratory.



### 5.3.6. External Survey

Experts from industry and academia were given the statement, “Compared to small groups, large groups do produce enough benefits to offset their costs for creative engineering design.” Responses to this statement were very mixed (mean = 2.4, standard deviation = 0.966). One respondent disagreed but said that the small group had to have the right type of people, appropriate expertise, and were good in communication.

The experts were also given the statement, “Large groups are more likely to generate more ideas per member than small groups.” Again the responses were very mixed (mean = 2.8, standard deviation = 1.229). The literature suggests that in the case of brainstorming, this is indeed the case. Of course, in this experiment, teams used nominal group techniques, not brainstorming.

### 5.3.7. Summary

In summary, there was a cost penalty associated with a large group size that was not offset by greater performance as the result of more team members. The task was solvable by many different concepts. The selection of a particular concept did not have implications for either system effectiveness or life-cycle cost. Group size did not have any significant effects on any of the components of system effectiveness. Group size had a significant effect on the direct labor portion of life-cycle cost but not the material component. Group size did not have a significant effect on process time. It did have a significant effect on process cost. The process losses created by larger groups more than offset access to a larger solution set from which to design the system and the ability to execute a better design more quickly.

## **5.4. Computer-Supported Cooperative Work**

The literature contains dozens of papers on the value of groupware to focus the efforts of members on the task, increase the depth of analysis, increase the task-oriented communication, increase the clarification efforts, increase decision quality, and increase the overall quantity of effort put in the decision process (Kraemer and Pinsonneault, 1990). However, no significance was found between the use of groupware and design performance, system effectiveness, or life-cycle cost, as hypothesized as shown in Chapter 4

In fact, few teams were enthusiastic about groupware. Survey responses to questions regarding groupware’s impact on team efficiency, effectiveness, productivity, and member contributions were in the “undecided” to “agree” range. In response to a question regarding overall satisfaction with the groupware process, the overall response across all conditions was 2.39 on a five-point Likert scale. The detailed data in response to all questions is provided in tabular and graphic form in Appendix E.6.

In debriefings of teams at the conclusion of the experiment, teams stated that the idea generation phase of groupware was fine. They believed that the ability to enter ideas simultaneously and anonymously was good. However, some building construction teams said that

they believed that the teams could have been more productive in a brainstorming mode. They said they could think better by reacting to others ideas rather than thinking on their own as in the nominal group process.

Teams felt that the interactive discussion of ideas through groupware stifled communication, produced less rich information, and was frustrating. Almost all participants in this experiment had excellent typing skills. Post hoc evaluations of a few teams showed that teams could communicate about five to ten times the amount of information per unit time orally than through groupware. Possibly groups felt frustrated because they were seated adjacent to each other. Had they been in different places, the frustration may not have been as acute.

Teams felt a need to communicate in symbols as well as text. This is a new finding in that groupware has not been previously studied with engineering groups. The software used had the ability to communicate via a whiteboard but that technique was not available to the teams in this experiment.

No teams reached true consensus at the conclusion of the groupware process. Oral discussion was permitted at the end of the groupware session (after voting) and it was during this phase that consensus was achieved. Teams knew at the conclusion of voting the degree of commitment to a particular concept. Yet it seemed that they need oral interaction to confirm the level of support for the idea.

Many teams expressed enthusiasm for groupware in future years to support different place, same time meetings, and different place, different time meetings. They could not see much value in groupware for same time, same place meetings.

The groupware software crashed during several trials. No data was lost but it may have had a frustrating effect on the participants.

#### 5.4.1. Groupware and Group Size

According to the Nunamaker, group efficiency, effectiveness, and satisfaction when using computer-supported cooperative work is enhanced as group size increases (Robinson, 1991). Efficiency is especially improved for groups that have eight or more members. Effectiveness is enhanced for groups of six or larger. Nunamaker states that small groups are more frustrated by groupware constraints, and are less likely to conclude that groupware is more effective or efficient than an unstructured face-to-face meeting. Larger groups appreciate the structuring inherent with groupware that keeps the group from becoming “bogged down” or subject to domination by member personalities.

#### 5.4.2. Effect on Process Time

Computer-supported cooperative work did not have a significant effect on overall process time as shown in Chapter 4. However, the process time of conceptual design when groupware was used significantly exceeded that of non-computer supported groups. The results of an ANOVA on this data show that the use of groupware,  $F(1,32) = 33.05, p < 0.001$ , and group size,  $F(1,32) = 27.91, p < 0.001$  were significant, as shown in Table 5.11.

Source	df	SS	MS	F	<i>p</i>
EM	1	7.22	7.22	0.16	0.695
CSCW	1	1525.22	1525.22	33.05*	0.000
GS	1	1288.22	1288.22	27.91*	0.000
EM*CSCW	1	30.62	30.62	0.66	0.421
EM*GS	1	119.03	119.03	2.58	0.118
CSCW*GS	1	70.22	70.22	1.52	0.226
EM*CSCW*GS	1	5.63	5.63	0.12	0.729
Error	32	1476.80	46.15		
Total	39	4522.98			

\*  $p < 0.001$

**Table 5.11. Conceptual Design Time ANOVA Table with Three-Way Interaction**

The ANOVA was recalculated eliminating the three-way interaction. There was no change to the significance levels of the main effects when eliminating the three-way interaction. The results of this ANOVA, shown in Table 5.12, show that the use of groupware,  $F(1,33) = 33.95$ ,  $p < 0.001$ , and group size,  $F(1,33) = 28.68$ ,  $p < 0.001$  were significant. The process time of groups that used groupware (mean = 49.40 minutes) significantly exceeded those that didn't (mean = 37.05 minutes). The mean for large groups (mean = 48.90 minutes) significantly exceeded the mean for small groups (mean = 37.55 minutes).

Source	df	SS	MS	F	<i>p</i>
EM	1	7.22	7.22	0.16	0.691
CSCW	1	1525.22	1525.22	33.95*	0.000
GS	1	1288.22	1288.22	28.68*	0.000
EM*CSCW	1	30.62	30.62	0.68	0.415
EM*GS	1	119.03	119.03	2.65	0.113
CSCW*GS	1	70.22	70.22	1.56	0.220
Error	33	1482.43	44.92		
Total	39	4522.98			

\*  $p < 0.001$

**Table 5.12. Conceptual Design Time ANOVA Table with Two-Way Interactions**

The fact that groupware had a significant negative effect on conceptual design time is very important. Groupware did not have the hypothesized positive effects of reducing the time required to reach consensus. This finding is contrary to most of the groupware literature.

On the positive side, an analysis of the results of the individual post experiment survey question (IPEQ#6) on conflict showed that computer-supported groups had less conflict (mean =

1.58) than non-computer supported groups (mean = 1.79). However, in this case the lower conflict did not result in less time spent achieving consensus.

Also as hypothesized, the process cost of computer-supported groups exceed that of non-computer supported groups. The results of an ANOVA on this data shows that the use of groupware,  $F(1,32) = 41.44$ ,  $p < 0.001$ , and group size,  $F(1,32) = 381.76$ ,  $p < 0.001$  were significant, as shown in Table 5.13.

Source	df	SS	MS	F	<i>p</i>
EM	1	18	18	0.02	0.885
CSCW	1	35462	35462	41.44**	0.000
GS	1	326706	326706	381.76**	0.000
EM*CSCW	1	456	456	0.53	0.471
EM*GS	1	2031	2031	2.37	0.133
CSCW*GS	1	9272	9272	10.83*	0.002
EM*CSCW*GS	1	6	6	0.01	0.936
Error	32	27385	856		
Total	39	401335			

\*  $p < 0.01$

\*\*  $p < 0.001$

**Table 5.13. Conceptual Design Process Cost ANOVA Table with Three-Way Interaction**

The analysis was repeated eliminating the three-way interaction. There was no change to the significance levels of the main effects when the three-way interaction was eliminated. The results, shown in Table 5.14, shows that the use of groupware,  $F(1,33) = 42.72$ ,  $p < 0.001$ , and group size,  $F(1,33) = 393.61$ ,  $p < 0.001$  were significant.

Source	df	SS	MS	F	<i>p</i>
EM	1	18	18	0.02	0.883
CSCW	1	35462	35462	42.72**	0.000
GS	1	326706	326706	393.61**	0.000
EM*CSCW	1	456	456	0.55	0.464
EM*GS	1	2031	2031	2.45	0.127
CSCW*GS	1	9272	9272	11.17*	0.002
Error	33	27391	830		
Total	39	401335			

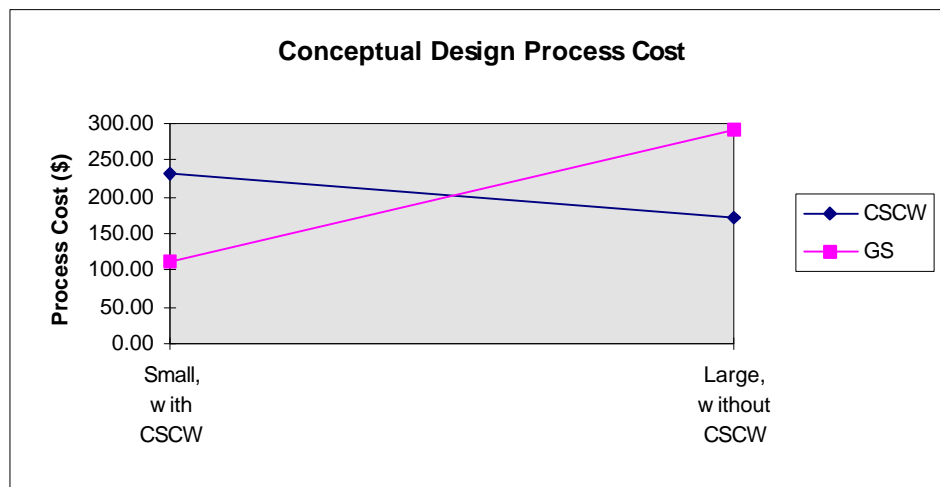
\*  $p < 0.01$

\*\*  $p < 0.001$

**Table 5.14. Conceptual Design Process Cost ANOVA Table with Two-Way Interactions**

The cost of groups that used groupware (mean = \$232.80) significantly exceeded those that didn't (mean = \$173.25). The mean process cost for large groups (mean = \$293.40) significantly exceeded those of small groups (mean = \$112.65). There was no significant difference between groups that used sequential engineering (mean = \$202.35) and groups that used concurrent engineering (mean = \$203.70).

The ANOVA also showed a significant interaction between groupware use and group size,  $F(1,33) = 11.17, p = 0.002$  as shown in Figure 5.9. The left of the chart represents the computer-supported, small condition. The right of the chart represents the non-computer-supported, large condition.



**Figure 5.9. Conceptual Design Process Cost Interaction**

The process cost in conceptual design of groups that were small and did not use groupware was substantially less (mean = \$98.10) than small groups that did use groupware (mean = \$127.20), large groups that didn't use groupware (mean = \$248.40), and large groups that did use groupware (mean = \$338.40).

#### 5.4.3. Effect on Participation

Groupware has been found to increase participation and decrease the domination of the group by one or few members (Kraemer and Pinsonneault, 1990). A SYMLOG analysis of the entire experimental process, not just the groupware process, showed that members of teams that used groupware had less difference between the most and least dominant member. The dominance difference for groups using groupware was 63.70 compared to groups that didn't use groupware (mean = 67.25). An ANOVA on this data showed that this was not significant. The range of values for dominance difference was from three to 134.

Another measure of participation is dominance dispersion. Dominance dispersion is the standard deviation of the dominance values for individual members of the team. Teams using groupware (mean = 22.368) had less dispersion than teams that didn't (mean = 23.022) but this was not significant. The range of values for dominance dispersion was from one to forty-three.

#### 5.4.4. External Survey

Most of the industry and academic experts contacted were not knowledgeable about groupware. The first statement in this area was, "Groups that use groupware are more satisfied with the group decision process than groups that use techniques like nominal group technique." Most respondents were undecided on this issue (mean = 3, standard deviation = 0.471 ). One respondent (Lentz, 1997) said that if groupware was defined as communication tools then the answer was, "yes." However, if groupware meant decision support tools then the answer was, "no." She says that she continues to believe that the hard problems get solved one at a time in eyeball-to-eyeball situations.

The second statement related to computer-supported cooperative work was, "Groupware is more effective for large groups than small groups." Again the respondents were somewhat undecided (mean = 2.8, standard deviation = 0.789). Lentz (1997) says that the response is, "yes", if the large groups are less collocated than small groups.

#### 5.4.5. Summary

In summary, the benefits of computer-supported cooperative work with respect to decision quality did not occur. The expected increased time and cost to use groupware was confirmed by this experiment. Groupware appears to be an emerging rather than mature technology. While its technological features are sufficient, there are social issues that have, as yet, not been resolved. The use of groupware in industry has not matured enough for there to be strongly held opinions about its value.

### **5.5. Limitations on Generalizability**

There was an indication that there may be a problem relating to the homogeneity of the population of teams used in this experiment. The six longest process times were recorded by engineering teams. Four of the five fastest process times were recorded by building construction teams. Based on the results of the *t*-test between the means of the cost effectiveness results of building construction and engineering teams, a more detailed analysis was performed. Two different analysis strategies were employed. The underlying approach of the first strategy was to separate the teams into two classes: (1) teams that only had building construction students on them, and (2) mixed teams, mostly of engineers but with other students including architects. Using this approach, the population of teams could be separated into two, twenty-team groups.

The second strategy was to separate teams based on the majority number of members. Using this approach, architect students were considered as if they were building construction students. The result of this process was the population of teams were separated into twenty four building construction teams and sixteen engineering teams.

The mean performance of building construction and engineering teams using both strategies was quite similar as shown in Table 5.15.

	BUILDING CONSTRUCTION	ENGINEERING
STRATEGY ONE	1.8680	1.4415
STRATEGY TWO	1.8610	1.3460

**Table 5.15. Comparison of Means by Strategy**

The following subsections present the results of these analyses.

#### 5.5.1. Strategy One

The rationale behind strategy one was that there was some underlying reason that building construction teams outperformed engineering teams and that reason was unique to only building construction students. Teams that had other than building construction students on them should be considered separately. This approach possibly overstated the cost effectiveness scores of the non-building construction teams but it permitted a balanced ANOVA analysis of all component factors of the experiment.

There was a significant difference between the cost effectiveness scores of the building construction teams and the engineering teams,  $F(1,38) = 4.22$ ,  $p = 0.047$ . The mean of the building construction teams was 1.8680 as compared to the mean of the engineering teams of 1.4415. The ANOVA table is presented in Table 5.16.

Source	df	SS	MS	F	<i>p</i>
Team	1	1.8190	1.8190	4.22*	0.047
Error	38	16.3716	0.4308		
Total	39	18.1906			

\*  $p < 0.05$

**Table 5.16. Cost Effectiveness ANOVA Table**

Since cost effectiveness is defined as system effectiveness divided by life-cycle cost, it could be expected that one of these variables would also be significant. They were not, however.

There was also a significant difference in process time,  $F(1,38) = 4.84$ ,  $p = 0.034$  as shown in Table 5.17.

Source	df	SS	MS	F	<i>p</i>
Team	1	2433.6	2433.6	4.84*	0.034
Error	38	19100.0	502.6		
Total	39	21533.6			

\*  $p < 0.05$

**Table 5.17. Process Time ANOVA Table**

Building construction teams were able to complete the experiment about fifteen minutes faster than the engineering teams. However, there was no significant difference in the time that it took one team or the other to perform conceptual design, detail design, manufacturing, or testing.

There was no significant difference in process cost between the two groups. This would be expected if there were no significant difference in process time.

There was no significant difference in the number of ideas generated per team or per person by both groups. The building construction teams achieved more successes with their systems than the engineering teams but it was not significant.

The building construction teams were significantly more satisfied with the processes used than the engineering teams,  $F(1,38) = 4.6$ ,  $p = 0.038$  as shown in Table 5.18.

Source	df	SS	MS	F	<i>p</i>
Team	1	0.9211	0.9211	4.6*	0.038
Error	38	7.6069	0.2002		
Total	39	8.5280			

\*  $p < 0.05$

**Table 5.18. Satisfaction ANOVA Table**

Table 5.19 summarizes the means for all of the variables considered by this analysis.



VARIABLE	BUILDING CONSTRUCTION	ENGINEERING
Cost Effectiveness	1.8680	1.4415
System Effectiveness	1330.6	1244.4
Life-Cycle Cost	798.80	971.00
Process Time	98.60	114.20
Process Cost	547.40	608.90
Ideas	4.9500	5.0500
Ideas per Person	1.1665	1.1580
Conceptual Design Time	42.25	44.20
Detail Design Time	45.50	55.90
Manufacturing Time	6.80	9.05
Testing Time	4.05	5.05
Successes	3.55	2.70
Satisfaction	1.9565	2.2600

**Table 5.19. Means for Various Variables**

### 5.5.2. Strategy Two

The rationale behind strategy two was that the team would perform in proportion to the majority of its team members. Architects were considered building construction students for the purpose of this separation since they were recruited from building construction classes. This approach required that an unequal cell ANOVA be performed on the data from twenty-four building construction teams and sixteen engineering teams.

Again there was a significant difference between the cost effectiveness scores of the building construction teams and the engineering teams,  $F(1,38) = 6.190$ ,  $p = 0.017$ , as shown in Table 5.20.

Source	df	SS	MS	F	<i>p</i>
Team	1	2.548	2.548	6.190*	0.017
Error	38	15.642	0.412		
Total	39	18.191			

\*  $p < 0.05$

**Table 5.20. Cost Effectiveness ANOVA Table**

Using the strategy two team structure, system effectiveness was not significant but life-cycle cost was,  $F(1,38) = 4.53$ ,  $p = 0.040$ , as shown in Table 5.21.

Source	df	SS	MS	F	<i>p</i>
Team	1	381444	381444	4.53*	0.040
Error	38	3199831	84206		
Total	39	3581275			

\*  $p < 0.05$

**Table 5.21. Life-Cycle Cost ANOVA Table**

As in the strategy one team structure, process time was significant,  $F(1,38) = 7.404$ ,  $p = 0.01$ , as shown in Table 5.22.

Source	df	SS	MS	F	<i>p</i>
Team	1	3511	3511	7.404*	0.010
Error	38	18022	18022		
Total	39	21533			

\*  $p < 0.05$

**Table 5.22. Process Time ANOVA Table**

Based on the means, as shown in Table 5.19, the building construction teams were able to complete the experiment about fifteen minutes faster than the engineering teams. However, there was no significant difference in the time it took one team or the other to perform conceptual design, manufacturing, or testing. Using this strategy, the time that it took to perform detail design was significant,  $F(1,38) = 4.152$ ,  $p = 0.049$ , as shown in Table 5.23.

Source	df	SS	MS	F	<i>p</i>
Team	1	1349	1349	4.152*	0.049
Error	38	12345	324		
Total	39	13694			

\*  $p < 0.05$

**Table 5.23. Detail Design ANOVA Table**

As was the case with strategy one, satisfaction was a significant effect,  $F(1,38) = 4.937$ ,  $p = 0.032$  as shown in Table 5.24.

Source	df	SS	MS	F	<i>p</i>
Team	1	0.980	0.980	4.937*	0.032
Error	38	7.547	0.199		
Total	39	8.528			

\*  $p < 0.05$

**Table 5.24. Satisfaction ANOVA Table**

An unbalanced ANOVA (2 x 2 x 2 x 2) adding the type of team to the basic experimental design was conducted to determine if there were any interaction effects between type of team and engineering methodology, group size, and use of computer-supported cooperative work technology. There were no two-way interaction effects.

As in strategy one, none of the other variables was significant, although in almost all cases the means of the building construction teams were better than the engineering teams.

### 5.5.3. Demographics

It was hypothesized that the demographics of the building construction teams as compared to the engineering teams might more accurately explain the difference in performance. There were more international students on engineering teams than building construction teams. Appendix E.10, Team Nationality Analysis, shows a breakdown of the teams by American and international students. Twenty-two teams or 55%, had at least one international student on them. Analysis of the performance of teams with international students on them as compared to teams without international students showed no significant difference in performance.

It was also hypothesized that the causal factor could be female students. There were more females on engineering teams than on building construction teams. Appendix E.11, Team Gender Analysis, shows a breakdown of the teams by gender. Eighteen teams (45%) had at least one female student on them. Twenty-four of the 180 participants in the experiment were female.

With respect to functional role-playing, five female participants were designers, eight were manufacturers, and eleven were support personnel. Analysis of the performance of teams with females on them as compared to teams without females showed no significant difference.

#### 5.5.4. Teamwork

A hypothesis was developed that one explanation for the difference between the two types of teams could be group dynamics. Possibly the building construction teams had better participation among members. An ANOVA was performed on the dominance difference values of the two types of teams. Dominance difference, a SYMLOG output, quantifies the amount of difference between the most dominant and least dominant person on the team. According to McLeod and Liker (1992) this is a valid measure of participation. There was no significant difference between the two types of teams.

Another participation measure according to McLeod and Liker (1992) is dominance dispersion. Dominance dispersion is the standard deviation of the dominance scores in a SYMLOG analysis. An ANOVA was performed on these values. There was no significant difference between the two types of teams.

Another hypothesis was developed that the building construction participants knew each other more than engineering students and hence, were more of a team prior to the experiment. An analysis was performed on the following statement from the Individual Post-Experiment Questionnaire: "I know my team members very well." The means from building construction teams (mean = 3.14) was similar to that of engineering teams (mean = 3.37).

#### 5.5.5. Summary

Whether the teams are classified according to strategy one or two, the building construction teams outperformed the engineering teams. The key variable that was identified in both analysis strategies was the effective use of time. The building construction teams were more completion focused and able to reach consensus on a variety of tasks much faster than their engineering counterparts. Faster times resulted in lower process costs due to labor, which were reflected in lower life-cycle costs, which resulted in higher cost effectiveness values. It appears that the superiority of the building construction teams was not the result of any single factor. The building construction teams did everything a little bit faster, a little bit better, and were more satisfied with the process than their engineering counterparts.

Therefore, are the results generalizable? Arguments can be made on both sides of this issue. An important question is who is the target audience for this research. If the target audience is engineering organizations, then it can be argued that the results are significant and generalizable even though the population was not homogeneous. The building construction students simply reduced the level of significance of the findings as a result of their effective and efficient use of time. Had they not been part of the population, the level of significance of cost effectiveness, time, and process cost would have been even greater.

If the target audience is architects and contractors then the results are not generalizable since it is difficult to predict whether cost effectiveness, process time, and process cost would

have been significant given a homogeneous population of building construction students. Without information on what made the building construction teams performance higher, it is difficult to make conclusions in this area. It is interesting to note that the highest performing team consisted of two building construction students and one engineer.

Another important issue relates to the group sizes employed in this research. Some would argue that both three and six person groups are small compared to most design groups in industry. Whether the results obtained herein are can be scaled to larger groups is debatable.

## **5.6. Analysis of External Survey Data**

Twenty-six survey instruments were sent to people in industry and academia that have written frequently on concurrent engineering or are otherwise very familiar with the engineering design process. Responses were received from ten people. Five surveys of fifteen sent to industry were returned. Five surveys of eleven sent to academia were returned. Two surveys were returned by the post office with incorrect addresses. These individuals no longer were employed at their companies. The mean number of years of experience in engineering design from the group that responded to the survey was twenty-two years.

The responses to the questionnaire are provided in tabular and graphical format in Appendix F.4. There was strong agreement that concurrent engineering shortens product development times (mean = 1.2), increases product quality (mean = 1.4), lowers the cost of production (mean = 1.5), and lowers the life-cycle cost of a product (mean = 1.3). All except one person agreed that the main tenet of concurrent engineering was the use of multidisciplinary or cross-functional teams (mean = 1.7). The experts also thought that groups that used concurrent engineering were more likely to be satisfied than groups that used sequential engineering (mean = 1.8).

There was less consensus that large groups produced enough benefits to offset their costs (mean = 2.4). Respondents didn't think that large groups were more likely to generate more ideas per member than small groups (mean = 2.8). Many respondents thought that groups that spent more resources in conceptual design would spend less in detail design (mean = 1.6).

The population selected for the external survey was not as knowledgeable about groupware as expected. Most of the responses to questions about groupware were undecided. The survey asked if groups that use groupware will be more satisfied with the group decision process than groups that use techniques like nominal group technique. Most responses were undecided (eight out of ten responses). Respondents were not sure whether groupware would be more effective for large groups than small groups (mean = 2.8).

Everyone strongly agreed that group dynamics was an important performance parameter (mean = 1.1). As one would expect from such an experienced group, many responses were provided with "it depends" qualifiers on them. Most often, the thing that "it" depended upon was the skill and experience of personnel and, in some cases, the culture of the organization.

### 5.7. Analysis of Building Construction Student Evaluation Forms

Evaluation forms were given to all building construction students that were participants in the experiment. Forms were completed by all students with the exception of one six-person team. The purpose of the form (see Appendix D.6.8) was to evaluate the suitability of the experiment, or one similar to it, in future building construction classes.

The first question on the form asked if the student thought that the exercise was relevant to learning about the design/construction process. Of the 106 respondents, 104 responded, “yes” (98%).

The second question asked if the student thought that the exercise should be included in future building construction classes. Of the 106 respondents, 102 responded, “yes” (96%).

The third question asked if the students responded “yes” to question 2, which class should it be included in. Since higher level students may have more insight in the appropriate class, Table 5.25 shows the current class of the respondents. Most students believe the Freshman level Introduction to Building Construction class would be preferable or have no opinion.

PROPOSED CLASS	CURRENT CLASS					Total
	5124 <sup>12</sup>	4444 <sup>13</sup>	4014 <sup>14</sup>	2024 <sup>15</sup>	1224 <sup>16</sup>	
Senior	2	4	1	1	0	8
Junior	0	1	2	1	1	5
Sophomore	1	4	1	8	2	16
Freshman	6	3	6	11	10	36
All	1	0	2	2	1	6
Any	0	0	0	1	0	1
Unknown	3	6	1	7	11	28
Other	1	0	0	0	0	1
<b>TOTAL</b>	14	18	13	31	25	101

**Table 5.25. Suggested Class For Experiment**

One question asked the participants to list some of the things that they learned from this exercise. Table 5.26 reports their responses as a function of their current class. Responses

<sup>12</sup> Land Development for the Constructed Facility

<sup>13</sup> Building Construction Practice

<sup>14</sup> Tech II - Environmental Systems

<sup>15</sup> Building Construction Principles

<sup>16</sup> Introduction to Building Construction

related to teams and teamwork were the most frequently mentioned things that they had learned. Given that the experiment was not designed to teach anything, this list is interesting.

	<b>CURRENT CLASS</b>					
<b>RESPONSE</b>	<b>5124</b>	<b>4444</b>	<b>4014</b>	<b>2024</b>	<b>1224</b>	<b>TOTAL</b>
Teams/Teamwork	8	10	10	16	14	58
Cost vs. Performance	0	1	2	3	3	9
Creativity	1	2	1	1	2	7
Groupware/NGT	3	3	1	4	0	11
Design Process	3	2	2	7	4	18
Communication	5	4	1	5	5	20
Time/Money Mgt.	2	2	2	9	3	18
Robustness	0	2	0	0	1	3
<b>TOTAL</b>	22	26	19	45	32	144

**Table 5.26. Concepts Learned from the Experiment**

The final question asked participants how the exercise could be improved to make it a better learning experience or more relevant to building construction. The preponderance of the answers to this question (36) related to making the problem a building construction or static problem, rather than a dynamic problem. Fourteen thought the exercise was fine like it was. Other suggestions included eliminating CAD, hold the experiment in class rather than at night, use different materials, give extra credit to the teams that perform the best, add more distractions and obstacles, and explain more in advance what is going to happen.

## **6. Conclusions**

### **6.1. Implications of this Research**

There is no doubt that companies today face stiff competition in a much more dynamic world than their predecessors. Majchrzak and Finley (1995) have identified a number of trends as we enter the new century. First, they believe there will be a globalization of technology and markets. Customers are becoming more demanding, sophisticated, and fragmented. They believe there is a trend toward smart products with fused technologies and software as major components. To be competitive, companies will have to be able to execute rapid product and process technology changes. They believe customers will more frequently intervene in the design of new products. Companies will form value-added alliances with other companies. And finally, there will be a trend toward more environmentally conscious manufacturing.

Each of these trends has implications for the design process. Products must be developed and, hence, designed more quickly. The voice of the customer must be clearly heard by those personnel making design decisions. Designers will have to adapt their products to meet the rapidly changing capabilities of the manufacturing and support functions. Likewise, manufacturing and support will have to be agile, flexible, and adapt to new product and process technologies. Organizations that optimize their technical and personnel resources in product development will have a competitive advantage to achieve success in the marketplace of the twenty-first century.

According to Karlsson (1995), the sociotechnical approach has been used to create more efficient engineering organizations. Teamwork, project organization and task groups are some of the approaches that have been used in combination with more structural methods such as concurrent engineering to improve the engineering process.

Optimizing technological and personnel resources will remain a continuous goal for successful organizations of the future. Technology is changing at an incredible rate. The personnel area, though not changing quite as quickly, is nonetheless changing. The purpose of this research was to add some rationality to some of the tradeoff issues that are applicable at this moment in time. The following sections describe how the conclusions of this research contribute to the current body of knowledge.

### **6.2. Contributions to Body of Knowledge**

This research empirically investigated three broad technological and personnel issues in the engineering design process. The target customer of this research was industry management. Management must make resource allocation decisions between deployment of technology or people to solve complex design problems with numerous constraints relating to time, budget, and requirements. This research is firmly grounded in sociotechnical systems theory which recognizes the interdependence of technical and social organizational subsystems. This research considered the effects of two technical variables, engineering methodology and the use of computer-supported cooperative work technology, and one organizational design variable relating to personnel, group size, on the engineering design process.



This research is believed to be unique from several perspectives. First, it was the first known attempt to simulate concurrent engineering in a laboratory setting. Other attempts to validate concurrent engineering superiority over sequential engineering have depended on action research. While the literature is full of anecdotal concurrent engineering success stories, each case contains dozens of confounding variables. Accurately simulating concurrent engineering design in a laboratory setting remains a worthy goal.

Concurrent engineering, to be successful, depends on the contributions of downstream functional team members to the design evolution. This research did not conclusively endorse concurrent engineering, even though all of the indicators were in that direction, because of the lack of vigorous participation in the design decision-making process by manufacturing and support personnel. This research has raised an important issue that has not been previously considered in the concurrent engineering literature. Good group dynamics is an important prerequisite to gaining the benefits that can be achieved through a concurrent engineering process.

Groups have been and will continue to be one of the most studied organizational entities. As problems become seemingly more complex due to the rapidly expanding base of data that should be considered, groups are necessary mechanisms to interpret, analyze, and convert data to information. Managers have to allocate scarce personnel resources to groups with the expectation that the benefits derived will offset the costs incurred. This research showed that for small engineering design problems, smaller groups are more cost effective than larger groups. Small groups were able to come up with enough design alternatives that one could be selected that would achieve the objectives of the system. Larger groups came up with more ideas, but not necessarily better ideas.

The expected benefits of CSCW technology did not occur in this decision-making exercise in engineering design. They were expected because CSCW technology has been successfully employed in a number of different settings. This research is believed to be unique in that no evidence of CSCW having been researched in a laboratory setting with engineering personnel has been found. It appears that the technology, in its current state of maturity, may be more successful with some types of people than others. This research showed that engineers are frustrated with its textual interface and desire a more symbolic interface. Engineers were not as satisfied with groupware as others in different settings have been. Although the overall research literature on satisfaction with the use of groupware is mixed.

Groupware has been found to increase participation and decrease the domination of the group by one or few members. This research showed that the dominance difference and dominance dispersion of groups that used groupware were less than those that didn't. This finding of this research is consistent with the current body of knowledge.

Other research has shown that groupware can increase or decrease the amount of time needed to reach a decision. This situation exists because of two opposite outcomes from groupware. Groupware can increase participation, thereby increasing time. Groupware can also cause the group to focus on the task, thereby reducing the needed decision time. This research supported the notion that groupware increased the time needed to reach a decision.

Decision quality has been shown to be an important benefit of the use of groupware. This research did not demonstrate that groups that used groupware made higher quality decisions.

This research is another example of the validity of sociotechnical systems theory and macroergonomics. Macroergonomics has not been previously considered in an engineering design environment. Yet, it is clear that the technological and personnel variables of this research are related. The relative success of engineering process methodologies, a technical variable, are a function of the number of members of the team, a social variable. Teams using computer-supported cooperative work, a technical variable, did not achieve the predicted improvements in performance as a function of group size, a social variable. Macroergonomics has therefore been shown to be applicable in another work environment.

Human factors engineers routinely make system design decisions that allocate functions of the system to either humans or machines (Price, 1985). In this case, the system is the engineering design process. This research showed that an allocation of resources to computer-supported cooperative work technology or increasing the number of people on a design team was not the most effective use of resources. Just because a technology exists or has the potential to substitute for humans, that is insufficient reason to make the substitution without careful tradeoff analysis.

### **6.3. Guidance to Practitioners**

It is recognized that any recommendations derived from this research are not necessarily applicable to all design organizations, all types of design teams, or all companies that perform design work. This experiment used a simple design problem that was solved by young engineering and building construction students. However, practitioners should not be too quick to dismiss the results. The responses to the external survey coupled with the laboratory results have provided more evidence of the validity of the results than might have otherwise been possible.

#### **6.3.1. Engineering Methodology**

One of the respondents to the external survey stated that concurrent engineering principles do work and represent the most significant single element in his company's success. Concurrent engineering has such strong face validity it begs the question of why it has taken industry so long to conceive and deploy it. While this research did not conclude that concurrent engineering was superior to sequential engineering, all of the various factors in the experiment like time and cost favored a concurrent engineering methodology.

This research did demonstrate that group dynamics plays an important role in achieving the purported benefits of a concurrent engineering approach. This experiment showed that when the manufacturing and support personnel did not advocate their goals, the design performance was lower. The exceptions to this finding were systems that by chance met the downstream goals. This research showed the effects of team members that disassociated from the team, lowering the effective group size and knowledge base with which the team had to work with. This research showed the effect of team members that dominated others, stifling their participation. Group dynamics play an important role in any engineering methodology. Therefore, practitioners need to ensure that members of teams have good team skills. Otherwise, the many benefits of teamwork will not be realized if some members of the team, or the team as a unit, act in dysfunctional manners.

### 6.3.2. Group Size

There are many different pressures on practitioners with respect to allocation of scarce personnel resources. Manager's need to ensure that the knowledge base and skills necessary to accomplish the task exist within the members of the team. In some cases, personnel are assigned to teams because they are available or need to be placed in positions that can be billed to a customer. This research demonstrated the diminishing returns of increasing group size, at least for tasks similar in scope to the task of this experiment. Practitioners should use as small a group of people as possible in teamwork situations. For example, it would be more productive to set up redundant small groups to solve a problem or make a creative decision than to consolidate them into a large group.

### 6.3.3. Computer-Supported Cooperative Work

Current advertisements on television tout that technology now permits a team to be productively scattered around the world. Numerous articles predict that many people will become telecommuters, working from home or vehicle. While the technology to achieve these things exists, this research suggests that there are losses when using computer-supported cooperative work. At a minimum, practitioners would be well-advised to experiment with CSCW in their environments before significantly investing based on the benefits touted by sales personnel. Based on this research, it is unlikely that CSCW employed in a same time, same place situation would be as productive as manual collocation methods.

Any assessment of technology that is being developed as quickly as collaborative technology has limited applicability. The technology will continue to improve and the expectation is that at some point in time, its benefits will offset its costs. In the meantime, practitioners should be skeptical and encouraged to experiment with it in their environments.

## **6.4. Further Research**

This research has raised many important additional questions. Issues related specifically to the independent variables of this research are considered in the following subsections. Overall opportunities for further research are presented in a concluding section.

### 6.4.1. Engineering Methodology

This experiment did not demonstrate the superiority of either concurrent or sequential engineering. Given industry and government's overwhelming endorsement of concurrent engineering, it is reasonable to question whether this experiment successfully simulated it. The experimental process used herein modeled one half of a complete concurrent engineering methodology - the downstream functional influence on the design process. What was not modeled was the design of the downstream processes. In this experiment there was no practical way to design a process for assembling LEGOs or a process for maintaining a system. If an experiment could be designed to take downstream process design into consideration, it would more accurately simulate a concurrent engineering methodology. Would adding this component of concurrent engineering significantly distinguish concurrent engineering from sequential engineering and more accurately simulate concurrent engineering in a laboratory setting? It is my

opinion that it would. However, the laboratory time would be substantially longer than the three hours used by this experiment.

One of the positive outputs of this experiment is a good database of cost information on systems that could achieve the design requirements. It would be a very interesting research project to reconfigure this experiment as an analysis of the merits of design to cost strategies. The essence of design to cost is making design converge on cost instead of allowing cost to converge on design (Michaels and Wood, 1989). According to Michaels and Wood (1989), by the year 2000, major high-technology enterprise will be dominated by those organizations that understand affordability and practice design to cost. Is design to cost a more cost effective design strategy than the engineering design methodologies used herein? The same experimental setup could be employed with the addition of cost targets as a system specification.

Teams in this experiment employed very unstructured processes for mapping the design requirements into features that would accomplish the requirements. Admitting that design is a creative process, Suh (1990) has proposed an axiomatic approach to design. He states that there are two design axioms that govern good design:

Axiom 1:     *The Independence Axiom*  
              Maintain the independence of functional requirements.

Axiom 2:     *The Information Axiom*  
              Minimize the information content of the design.

Axiom 1 means that in an acceptable design, the design parameters and the functional requirements are related in such a way that specific design parameters can be adjusted to satisfy its corresponding functional requirement without affecting other functional requirements. Axiom 2 means that the best design has the minimum information content or the least complexity. Suh proposes a design process that relies less on creativity and more on process execution. This experiment could be used to test Suh's axiomatic approach. Do teams that employ Suh's approach design more cost effective systems? This research could be performed using the same experimental setup. Teams could be trained in Suh's methodology and their performance compared to the current research results.

The issues raised by this research related to goal-sharing also have potential for further research. Management certainly expects open and honest communication among team members. As was shown in this experiment, there are circumstances which cause team members to act individually. While this line of inquiry will undoubtedly lead to sociological considerations, it is nonetheless an important issue for managers trying to maximize the contributions from all team members. Why don't team members act like a team? This research is also suitable for laboratory testing.

#### 6.4.2. Group Size

This research conclusively demonstrated the benefits and costs of three person and six person teams in the solution of creative design problems. It would be interesting to conduct this experiment with four and five person groups. This would either confirm or refute Hare's (1976)

notion that five members is the optimum group size. Is there a linear relationship between performance and group size? This experiment could be repeated with different group sizes.

This research considered six person groups as large groups because the literature states (Hare (1976:1992)) that groups larger than six tend to decompose into subgroups of six or less members. In reality, there are many groups formed to do engineering design that are quite large. If larger groups could be practically employed in this experiment, the potential benefits of computer-supported cooperative work might begin to offset the larger group process losses. One respondent to the external survey suggested that large groups were groups with more than fourteen members. Can the experiment be modified in such a way that research can be conducted on very large groups? In order to productively employ more people, the task would have to be made more complex with more deliverable products. Otherwise, a larger group would simply stand around and watch the more dominate members of the team solve the problem.

#### 6.4.3. Computer-Supported Cooperative Work

There are a number of areas of possible future research related to computer-supported cooperative work given this experiment's overall lack of endorsement of this technology. Many engineering and building construction students expressed frustration with having to communicate textually. Even simple designs can be difficult to accurately communicate among team members. Many teams felt that engineering teams need to communicate symbolically rather than through the textual interface imposed by this experiment. Would CSCW have been more satisfactory to engineering and building construction teams if it contained a sophisticated graphical communications system? This experiment could have employed an electronic whiteboard feature in groupware. A much smaller experiment focusing on communication among product development teams could be developed.

Many teams were frustrated by having to communicate with people through groupware that they could literally reach out and touch. Given the same experimental setup, members could have been located in different places. Would the frustration with groupware have been lessened if they couldn't see each other? Given the completion of other on-campus laboratories with groupware, the conceptual design phase of this experiment could be performed by virtual teams.

Design problems are often not solved in a same place, same time manner. Data needs to be gathered. Creativity takes time. If the experiment could be adapted for a longer elapsed time, it would be possible to use CSCW in a different time, different place senario. Would teams have designed more cost effective systems given less time pressure? Would the use of groupware for "different place, different time" discussions have been more satisfactory to the participants?

Nominal groups have been shown to be a more effective form of group. This research was designed to compare nominal groups using groupware and manual groups using a nominal group technique. Many participants suggested that design was more appropriately done in a brainstorming mode. Since groupware has a brainstorming feature, would the use of groupware as a brainstorming tool have been more successful than its use as a nominal group technique tool? This could be simply considered by using the same experimental setup for the conceptual design phase but using groupware's brainstorming feature.

The data indicated less conflict among members of computer-supported groups. This could be positive or negative. Positive conflict is necessary for resolution of design tradeoffs. If

the groupware was so challenging to use that the manufacturing and support personnel chose to not advocate their goals then the lack of conflict was a bad thing. If the use of groupware mitigated negative conflict then that would be a good thing. Does groupware support positive conflict or mitigate negative conflict? A content analysis could be performed on the existing data or a similar experiment to consider this issue.

Groupware significantly increased the time to perform conceptual design. Conceptual design in the context of this experiment was simply technical decision-making. Ideas were generated individually, their merits were discussed, albeit through computers, and a decision made. Groupware could have reduced the time to reach consensus, as described in the literature, rather than increased it. Did groupware increase the time because of the nature of the problem to be solved, the characteristics of the participants, or some other factor? Groupware is thought to be more valuable for more complex problems. A similar experiment could be developed in which the degree of difficulty of the task was an independent variable.

#### 6.4.4. Overall Research

Building construction teams outperformed engineering teams on the task of this research. Given the commitment of contemporary organizations to team-based structures, it is important to understand this phenomenon. Does it somehow relate to their educational experiences? Are the demographics of the teams (e.g., international students) the real differentiation in performance, even though this issue was not confirmed by this research? This issue is of such importance that research focusing simply on this issue should be pursued. The outcome could have very positive effects on engineering curriculums and our understanding of technical teams.

SYMLOG, as a group dynamics assessment tool, did not adequately differentiate teams that were comprised of members that were so similar in personality. Team member assessment is a critical industry need. How can SYMLOG be improved to more accurately assess the group dynamics of engineering design teams? Can better group dynamics methods of assessment be developed?

While this research was not focused on team leadership, the issue was considered in survey questionnaires and in the final debriefing with each team. Most teams felt that on a problem as small as this one, a leader would have stifled teamwork. Yet they all felt that if someone had been in charge the process could have been concluded more quickly and efficiently. Team leadership of small groups is an important issue. Should small teams have assigned or emergent leaders?

#### 6.4.5. Action Research

Industry and government are presently implementing many of the concepts of this research: concurrent engineering, teams, computer-supported cooperative work. There are now opportunities to continue this research in the field. For example, the Jet Propulsion Laboratory (JPL) has created a Project Design Center (PDC) for multifunctional teams to concurrently design new space missions and prepare proposals. This conceptual design center is able to accommodate up to forty people that are linked by computer-supported cooperative work technology. Teams have access to discipline-specific tools like structural analysis, as well as tools that permit macro-

level tradeoff analyses. The PDC would be a great research environment to continue the analysis of personnel and technological tradeoffs.

## **6.5. Summary**

Research on engineering design is a rich area for development of new understandings about creative processes, how teams really work, and, most importantly, how technology and personnel interact. The challenges of our rapidly changing work demand that we continuously seek new methods for creating, designing, and manufacturing new products while unlocking human potential. We are nowhere close to a theory of engineering design. Only by continuing to conduct research on its many facets will others be able to understand how to develop the products that satisfy the needs of the future.