A Double-Edged Sword: Relationships between the Engineering Use of Computer Tools and Project Performance

by

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S.B., S.M. Electrical Engineering, MIT (1977)
S.B. Humanities & Science, MIT (1977)

Submitted to the Sloan School of Management in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY in Management of Technological Innovation

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ABSTRACT

Field research in the nature of engineering work, and the relationships between the use of computer tools and project performance, was conducted over a two-year period at two U.S. R&D firms. A triangulation technique consisting of participant observation, interviews, and questionnaires was used to collect data from engineers working in thirty-two different projects.

Although engineers do many different kinds of work, such as manufacturing support, communication, and management, engineers in the study spent about 45% of their average work day performing the kinds of work traditionally associated with the engineering profession, such as analysis, design, and development. Because engineering is also a group-oriented activity, engineers spent a substantial part of their day (about 40%) communicating in some way (including technical documentation).

Engineers with access to more sophisticated computer tools in their immediate work area are more likely to use these tools in their work. Projects whose engineers make greater use of computer tools are also more likely to be under budget after controlling for the effects of moderating variables such as the level of required technical sophistication, the phase of the project, and the quality of project work.

Given their capabilities and limitations, today's computer tools do not always leverage engineering productivity. Use of computer tools for analysis work, early in the engineering design and development cycle, was found to be negatively correlated ($r = -0.30$) with innovativeness. By contrast, use of computer tools for engineering development, later in the cycle, was found to be positively correlated ($r = +0.35$) with innovativeness.

Computer tools are like a double-edged sword. Properly managed, they can shorten development time, improve the efficiency of individual contributors, and reduce support staff requirements, permitting more thorough evaluation of design options and allowing more time to be spent in creative activity.

However, computer tools can have equally detrimental effects. Because of the tendency of computer tools to encourage "cloning" solutions to old problems, use of these tools can lead to homogeneity of engineering designs, stifling innovativeness. Use of inappropriate or inadequate tools can also detract from engineering performance.

Thesis Supervisor: Professor Thomas J. Allen

Title: Gordon Y. Billard Fund Professor of Management

BIOGRAPHICAL NOTE

Dave received the Bachelor of Science and Master of Science degrees in Electrical Engineering and Computer Science from MIT in January, 1977. Concentrating his technical studies in instrumentation and automatic control, he worked in the Spacecraft Preliminary Design group of RCA's Astro-Electronics Division in Hightstown, New Jersey on work-study. His Master's thesis, "Application of Modern Control Theory to the Design of an On-Orbit Attitude Control System for a Three-axis Spacecraft with a Controlled Flexible Appendage", was published as an RCA Technical Report in May, 1977.

A double-major, he also received a Bachelor of Science in Humanities and Science in January 1977, majoring in English Literature and Creative Writing, and minoring in Theoretical Mathematics. *The Central Highlands Collection*, poems on the Vietnam War, won the Boit Prize in 1976. A seasoned debater, he holds the Degree of Distinction from the National Forensic League.

Upon completion of his studies in 1977, Dave began a five-year active duty assignment as a commissioned officer in the United States Army, attaining the rank of Captain. He served as both Combat Engineer Officer and Intelligence/ Electronic Warfare Officer with the 4th Brigade, 4th Infantry Division in Wiesbaden, Germany, and was the Brigade S-2 (Chief of Intelligence and Security) during 1981. While on active duty, Dave studied management with the University of Southern California's School of Systems Management.

In 1982, Dave returned to civilian life and the RCA Corporation, working as a computer and communication systems engineer with the Automated Systems Division in Burlington, Massachusetts. While at RCA-ASD, he became a lead user of personal computers in engineering work, and became very interested in the relationship between computer tools and engineering performance. In 1983, he entered the Ph.D. program at the MIT Sloan School, undertaking a multi-disciplinary course of study and research spanning technology management, information systems technology, and man/machine interface design. Dave also continued working part-time as a systems engineer with RCA and GE, with complete funding for his studies provided by the RCA and GE Corporate Graduate Study Programs. He currently works with a Sanders•GE advanced-technology joint venture team in Nashua, New Hampshire, where he manages about $2 million of work annually in the areas of operations analysis, requirements development, and engineering design trade studies for integrated electronic warfare systems (INEWS). Dave is also the Project Engineer for the Naval Advanced Tactical Fighter (NATF) Electronic Combat system.

Dave was born in Honolulu, Hawaii, and is a 1971 graduate of Immaculata High School, Leavenworth, Kansas. He lives with his enchanting wife Tommie, four children (Amanda, Susan, Allen, and Barbara), dog (Frodo), and four cats (Greymantle, White One, Einstein and Gwen) in Nashua, New Hampshire. He is an ardent player of role-playing games like Dungeons and Dragons, and loves to build and play musical instruments, make airplane models, write science-fiction and fantasy, and compete in high-powered rifle matches.

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CHAPTER 1. INTRODUCTION AND RESEARCH METHODS.

Understanding the relationship between computer tools and engineering project performance first requires a thorough understanding of the nature of engineering work, both at the individual and project level. What kinds of tasks do engineers perform? How much time do they allocate to performing them? What sort of computer tools do engineers use? To what extent are they used? And how is the use of computer tools by engineers related to technical performance at the project level?

The **goals of the research** are twofold. First, we seek to improve our understanding of the engineering work process and engineering use of computer tools, using a triangulation of qualitative and quantitative techniques:

1. Develop a **taxonomy** of engineering work tasks by observing engineers, and studying the process of engineering work (Appendix D). This is done through an ethnographic study using the participant observation method at two field sites employing engineers.

2. Develop **time profiles** of engineering work, and engineering use of computer tools. This is done through statistical analysis of sample data collected from engineers using questionnaires distributed at the two field sites.

Second, we explore the correlation (if any) between engineer's use of computers, and the performance of projects. This is done through the evaluation of **three hypotheses**:

1. Given access, computer tools are used more by engineers when more sophisticated tools are available.

2. Use of computer tools is related to **increased productivity** at the project level, as measured by performance of the project against its planned schedule and budget.

3. Use of computer tools is related to **better technical performance** at the project level, as measured by ratings of technical quality and innovativeness of engineering work.

RESEARCH PROGRAM DESIGN.

The research began in 1985 at Company 1, a federal systems division of a large technology-based conglomerate. Located in New England, Company 1's fourteen hundred employees design and manufacture computer-based products for the defense market (Appendix A). A triangulation technique, combining qualitative, ethnographic studies (participant observation and personal interviews) with more quantitative methods (stratified random sampling of the engineering population using questionnaires and statistical analysis), was used to gather and analyze data on engineering work, engineering use of computers, and project performance. Although work-intensive for the researcher, the triangulation method blends the flexibility and insight offered by participant observation and interviews with the data collection efficiency of questionnaires. Questionnaires for collecting data on engineering work and computer use time allocations, engineering backgrounds, and project performance were developed based on insight gained from the qualitative phase of the research. The questionnaires were then used to gather data from over a hundred engineers and project leaders on work and computer use time allocation (1985, 1987, 1988), engineering backgrounds and job categories (1987, 1988), and project performance (1988) (Figure 1).

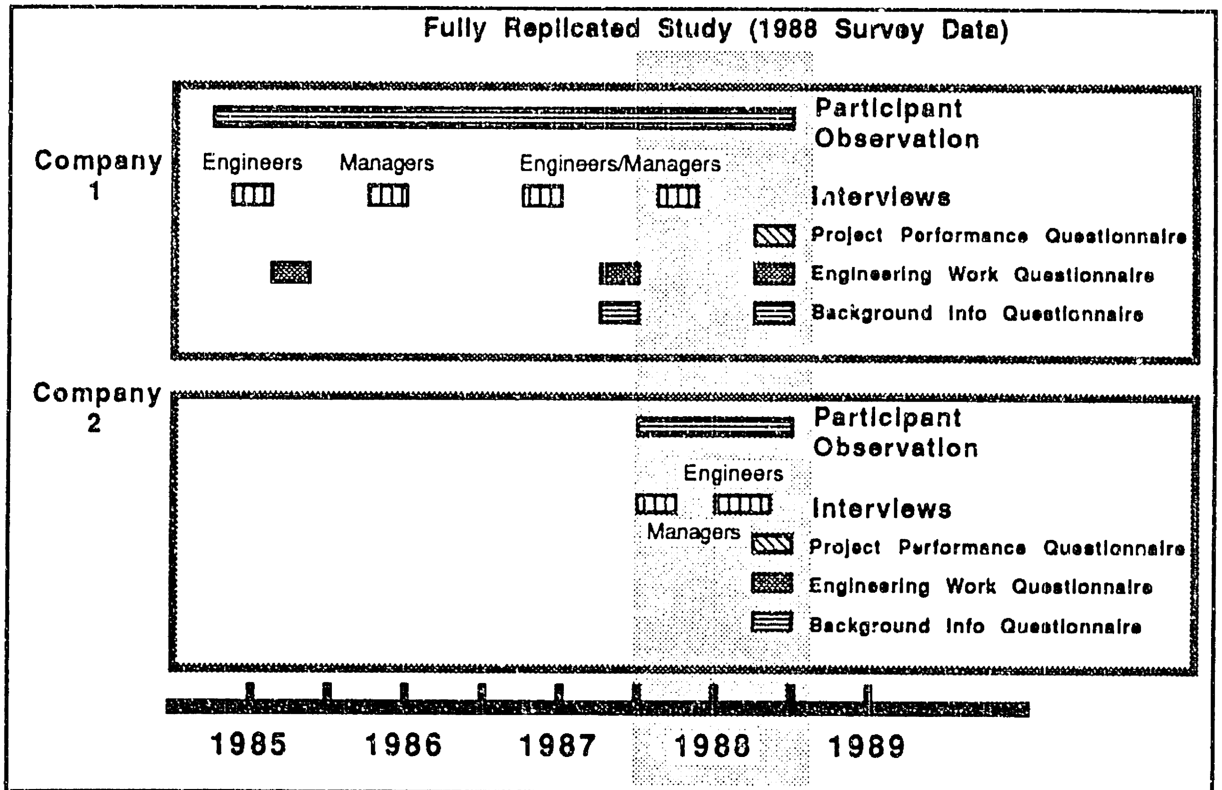


Figure 1. Multi-year experimental design. The study was fully replicated at a second site during the last year of the data collection.

An opportunity arose in mid-1987 to **replicate** the experiment at a second site. Company 2 (the R&D division of a commercial computer company with world-wide branches) has approximately the same number of employees as Company 1, and is also located in New England. However, while Company 1 competes in the defense market, Company 2 primarily competes in the commercial market. More importantly, as a CAD/CAM pioneer with major market share in the computer workstation market, Company 2 has aggressively pursued the goal of a **paperless office and lab** environment for its engineers, and has created a Computer Aided Engineering (CAE) environment that is a model for the industry (Appendix B). Each engineer, manager, and secretary has a powerful workstation on his or her desk. The workstations are networked with file servers (shared high-capacity disk drives), print servers (shared printers), and other computers using a high-bandwidth local area network (LAN). High-bandwidth LAN's bridge networks between buildings, while high-speed telephone data lines link Company 2's network with other corporate sites.

The study begun at Company 1 was fully replicated at Company 2 during the last year of the data collection cycle (Figure 1). Questionnaires developed at Company 1 were modified for consistency with Company 2's corporate terminology, and were distributed and collected electronically over the network. Data samples of engineering work, computer use, engineer background, and project performance were collected in parallel with Company 1, where paper forms and internal mail were used for questionnaire distribution and return. Empirical data on approximately 3500 man-hours of engineering work and thirty-two projects were collected.

The collection, aggregation, and analysis of data to analyze the relationship between engineering work, use of computer tools, and project performance is a complex, multiple-step process (Figure 2):

Step 1. Collect Engineering Work and Computer Use Data from Engineers.

Two questionnaires were distributed to the engineers at the two firms. A background questionnaire was distributed once to each engineer in the sample population. This questionnaire collected demographic data about the engineer, including information on the type of work (e.g. hardware, software, management, etc.) being done by the engineer, their experience with computers, as well as the availability of computer tools both at work and at home.

A second questionnaire (Figure 5) was sent to each engineer once or twice per month on a randomly selected work day. On this questionnaire, the engineer was asked to record:

- the number of hours worked in each of a dozen work categories that day;
- the number of hours computer tools were used in each of those categories on that day;
- which of ten hardware and ten software tool types were used to support each of those work types on that day;
- the number of hours spent on various projects that day, identifying the project by project name (or project ID) and manager name.

Step 2. Collect Project Performance Data from Managers.

Once a project manager was identified by one or more engineers, that manager was sent a project performance questionnaire (Figure 18), and asked to categorize his or her project by size, phase, level of technological sophistication required, etc. The manager was also asked to rate the project in terms of four measures of performance: quality of work, innovativeness of work, budget performance, and schedule performance. The manager was NOT asked any questions about computer use by engineers on the project. (The manager may have received, separately, the sampling questionnaires sent to the engineers.)

Step 3. Analyze the Use of Computers, and Factors Correlated with their Use.

Some engineers use computer tools more than others, or use them for different kinds of work. Factors such as the availability of tools, resource contention, and training may be substantially correlated with computer use. Such factors may also be extraneous or intervening variables which could affect the correlation between computer use and project performance.

Step 4. Analyze Project Performance, and Factors Correlated with Performance.

It would be naive to believe that computer use by engineers is the sole driver of project performance. Numerous factors, like project phase or the level of technical sophistication required in the project, may affect quality, innovativeness, schedule, and budget. Further, the four measures of performance may not be totally independent; innovative work may be viewed as high quality work, while high quality work may cost the project time and money resulting in schedule slips and budget overruns.

Step 5. Aggregate Engineering Work and Computer Use Data by Project.

This is an important step. The unit of analysis for the engineering work and computer use data is the individual engineer (identified by a unique serial number), while the performance data is at the project level (identified by a unique project number). To shift the unit of analysis from the individual engineer to the project team, the computer use data sets must be weighted by project participation hours and aggregated, grouping them by project (Figure 2).

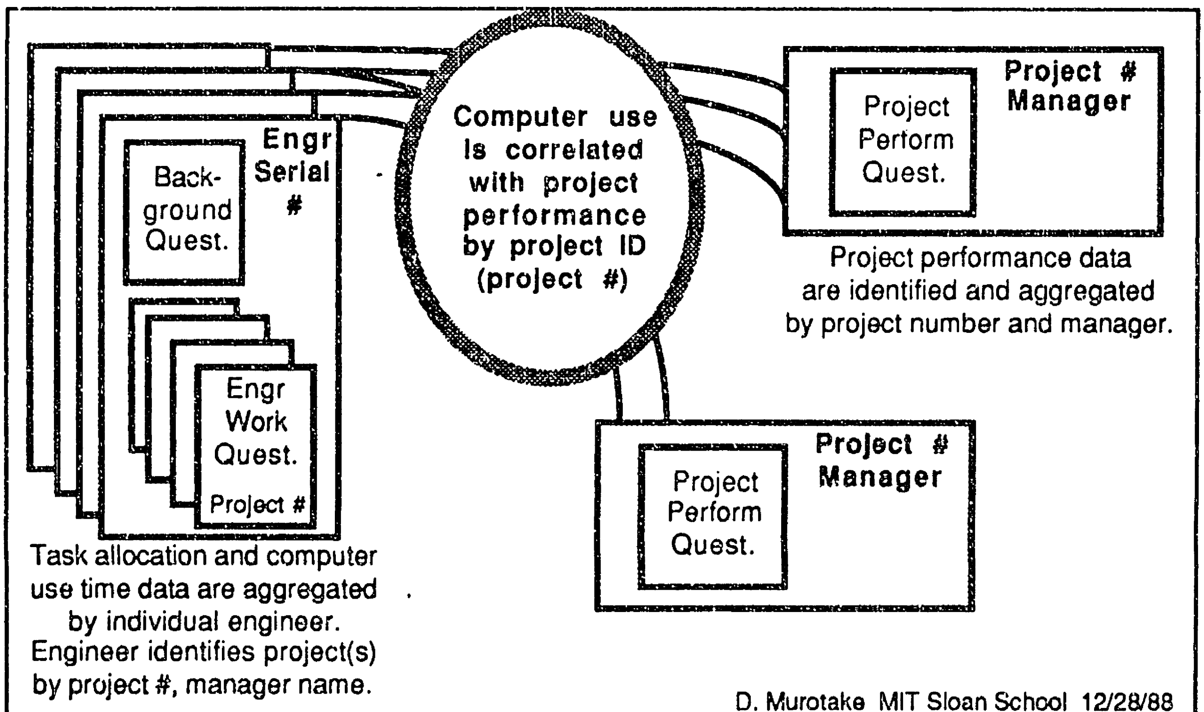


Figure 2. The unit of measurement shifts from the engineer to the project when analyzing project performance. Computer use and other data from individual engineers are weighted by the amount of project contribution time, and aggregated by project with performance data from project managers.

Step 6. Correlate Project Performance with Computer Use.

Aggregation of the engineering work and computer use data by project permits the final step, partial correlation of computer tool use with project performance while controlling for intervening and extraneous factors. This allows the testing of the two hypotheses relating computer use with increased productivity and technical performance.

CHAPTER 2. ENGINEERING WORK.

In this chapter, we review the literature on the nature of engineering work and technical problem-solving, present a taxonomy of engineering work developed through participant observation, and report on the allocation of time by engineers to different kinds of work, based on survey data from two research sites.

LITERATURE REVIEW.

The Nature of Engineering Work.

Engineering is a technical problem-solving activity resulting in the design and development of technical products (space shuttles, surgical lasers, automobile tires) and processes (petroleum distillation, silicon crystal growing, titanium welding). Engineers are the salaried technical professionals specially trained for, and hired to perform, engineering work. Engineering work is richly multi-disciplinary, spanning scientific experimentation, mathematical analysis, design and drafting, building and testing of hardware and software prototypes, technical writing, marketing, and project management (Ritti, 1971). Engineers usually work as members of a project team.

Engineering work is a form of research and development (R&D) activity. Allen, Lee & Tushman (1980) categorized R&D related work as being either:

1. Basic research.
2. Applied research.

3. Development.
4. Technical services.

Basic research is concerned with the development of fundamental knowledge. Applied research, on the other hand, is devoted to bringing the fundamental knowledge to the point of useful application. In development, innovative products or processes are brought to the point of practical use in the real world (as opposed to laboratory) environment. Technical services apply technical problem-solving to "production" and "maintenance" projects. Engineers are employed in all four categories of R&D work, although most work in the second, third, and fourth categories.

Ritti (1971) describes engineering as a problem-solving cycle consisting of:

1. Experimenting.
2. Analyzing.
3. Designing.
4. Building.
5. Testing.

Technical Problem Solving and Design.

The genesis of engineering work is the identification of problems which need solving, and ideas on how best to solve them. Engineers scan both the technical and market environments, seeking out problems in need of solutions, and technologies with which to solve them. In a study of over 500 technical innovations, the recognition of market demands (75%) and technical feasibility

(21%) were shown to be important factors in technical innovation (Marquis, 1969).

Central to engineering work is design, consisting of a sequence of critical consideration of various ideas, predictions of outcomes for each idea, and evaluation of outcomes using selected criteria. Parallel examination of ideas is preferable, both for speed of solution and an improved insight into the problem (Marples,1961). One method of solving engineering design problems is the decomposition of a problem into several levels of subproblems (Allen, 1966a). This decomposition, or transformation, occurs until pattern recognition identifies a subproblem as being "similar to" a previously solved problem, whereby the problem is solved by analogy (Anderson, 1985). Another method of solving design problems is through the use of association, freely browsing between related topics (not necessarily on the "correct" solution tree) in hopes of finding a serendipitous solution (Fiderio, 1988). Allen (1977) suggests that engineers preferentially consider solutions to previous, similiar problems as solutions to current problems; this body of existing solutions forms a "positive/negative biasing set", and may lead to the choice of suboptimal problem solutions.

Non-technical Components of Engineering Work.

Engineering work is not entirely devoted to technical problem-solving. It has substantial non-technical components, such as office communication, management, and administrative work. Strassman of Xerox, discussing plans for an office automation system, put it this way:

In engineering and design departments of corporations, you're lucky if people spend 20 percent of their time on technology. They spend most of their time in meetings - progress meetings, budget meetings. Society is vastly unproductive administratively. That's a prime cause of inflation. But we're going to fix this. We are going to really go after the administrative overhead, lower prices, increase demand, and become competitive. (Schlefer, 1983)

The belief that engineers only spend 20 percent of their time on technology related tasks found support in a pie chart (Figure 3) based on an internal study of 400 engineers at HP-Ft Collins. This chart, and others like it, received wide distribution in 1984 and 1985 through sales brochures for computer aided engineering tools, being cited as a "typical" engineer's time profile (Miller & Kelley, 1984).

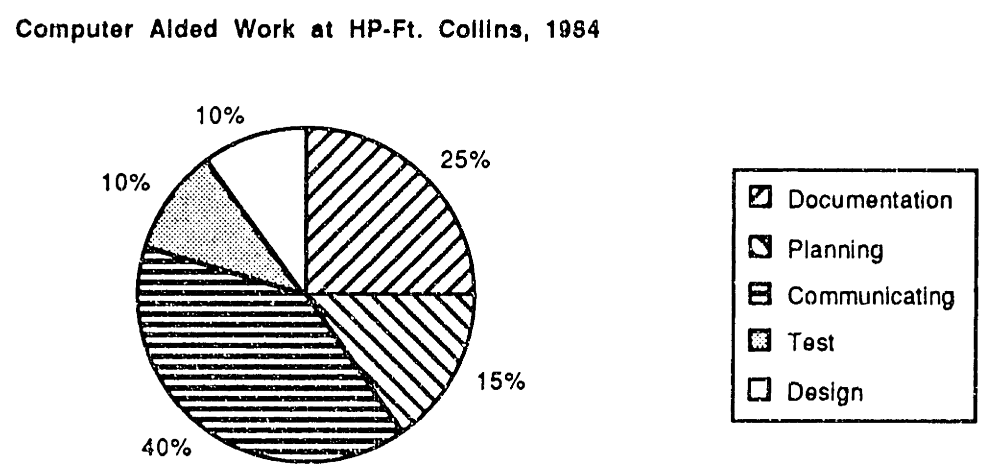


Figure 3. Pie chart of engineering work time allocations, based on an internal study of 400 engineers at HP at Ft. Collins, Colorado, and cited in a study by Miller & Kelley (1984). This pie chart received wide circulation as a "typical" engineer's time profile during the mid-1980's.

The Group Nature of Engineering Work.

Design and development of complex technical products are usually performed by project teams cooperating to achieve common technical objectives (Marples, 1961; Allen, 1966a). Engineering project dynamics (interactions between engineers, managers, customers, and external environment) can be complex (Roberts, 1974). The process of engineering work is not only a technical one, but a social one in which management, communication, and motivation influence the efficiency, quality and innovativeness of the project team's work.

THE RESEARCH SITES.

The participant observation and statistical sampling for the study of engineering work and project performance was done at two different electronics firms in the United States. Both firms employ several hundred engineers, and gross over $250 million a year in division sales.

Company 1 is a federal products division of a large technology-based conglomerate. It is a "system integration house" (sometimes referred to as a "rack and stack" house), taking major components built by other companies (such as computer CPU's, disk drives, monitors, modems, software applications, etc.) and integrating them into complete and working systems, often crafting special software and hardware for this purpose. The company operates in four heavily competed niche markets, where the discriminating factors for success are price, innovative design, skill base, and cost/schedule performance on previous government programs. These systems are designed to stringent government cost and performance specifications.

By contrast, Company 2 is the R&D division of a manufacturer (with substantial market share) of computer workstations, networks, and software. Company 2 operates in a highly competitive commercial market, which it seeks to dominate through innovative, high quality. cost effective product lines and an ability to recognize and serve the needs of a diverse clientele.

ENGINEER CHARACTERISTICS.

Substantially different corporate cultures and work environments complicate inter-site comparisons (Appendices A.1 and B.1). These differences are reflected in data collected by the Background Questionnaires at the two research sites (Table 1). Differences in automation level between the two companies is a tempting implicit moderator, although caution must be exercised when making inter-site comparisons between, or cumulations of, sample data collected at the two sites.

Engineer Demographics	Company 1 Sample Mean	Company 2 Sample Mean
Sample Population Size:	N=92	N=24
Job Category		
Electrical Engineer	26%	0%
Software Engineer	23%	67%
Mechanical Engineer	20%	0%
Systems Engineer	12%	0%
Manager	10%	29%
Other	10%	4%
Gender		
Male	91%	88%
Female	9%	13%
Position Title		
Jr Technical	36%	4%
Mid Technical	28%	50%
Sr Technical	20%	17%
Management	16%	29%
Previous Experience		
Electrical Engineering	55%	29%
Software Engineering	38%	96%
Mechanical Engineering	30%	4%
System Engineering	30%	33%
Management/Marketing	18%	33%

Table 1. Sample means for selected engineer demographic factors at the two research sites.

Engineers frequently have technical work experience outside their current career specialization (Table 1). For instance, although only one-fourth (26%) of the engineers surveyed at Company 1 are currently electrical engineers, over half (55%) have previously been employed as such for at least one year. Note, too, that almost all (96%) of the engineers surveyed at Company 2 (including the 29% currently working as managers) have software engineering experience.

DEVELOPING A TAXONOMY OF ENGINEERING WORK TASKS.

Participant Observation.

A taxonomy of engineering work was developed from observational data obtained through participant observation performed at both companies. At Company 1, I was employed as a systems engineer, and spent half my time over a five-year period observing and participating in engineering work as an engineer. Research access to four engineering sections, with 187 engineers and their managers, was granted by Company 1 management. (Note: Of these engineers, 108 (58%) chose to participate in the study by agreeing to interviews, or by responding to questionnaires distributed during 1987 and 1988.)

At Company 2, I gained access as a university researcher. I spent half my time over a nine-month period meeting and observing engineers and managers, and learning about their work and computer tools. During this period, I was assigned a "mentor" (an experienced engineer who got me started, and gave advice or rescue as needed), office, desk, workstation, electronic mail account (including membership on several lists, which guaranteed lots of EMAIL), phone, and name plate. I had access to engineers and their managers in the company's R&D group. Thirty-five engineers volunteered to participate in the engineering work study, responding to questionnaires distributed during 1988.

The Taxonomy - Thirty One Tasks.

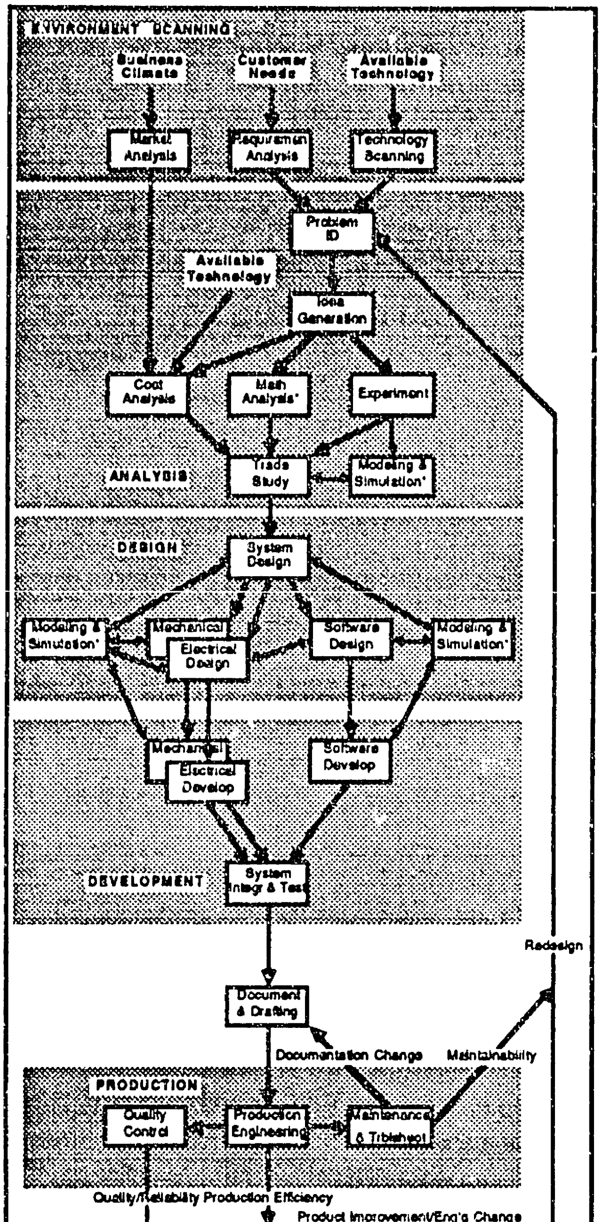


Figure 4. The Engineering Cycle.

These "generic" task types, common to several hundred other subtasks, number over thirty (Appendix D and Table 2). Figure 4 shows where these tasks fit in the engineering work cycle. (Not shown are communications and management tasks, which are necessary to ensure the efficient flow of the other tasks.) The tasks are diverse, ranging from technical design, development, and test (traditionally associated with engineering work) to management, manufacturing, communications, and market analysis. The tasks have been grouped into eight categories: environmental scanning, analysis, design, development, production, management, communication, and other tasks (Table 2).

Environmental Scanning	Analysis
Market Analysis Requirements Analysis Technology Scanning	Problem Identification Idea Generation Experimentation Mathematical Analysis/Simulation Cost Analysis Trade-off Analysis
Design (Synthesis) Mechanical Design Electrical & Electronic Design Software Design Overall System Design	**Development (Synthesis)** Mechanical Prototyping Electrical & Electronic Prototyping Software Coding & Debugging Overall System Integration
Production Production & Process Engineering Quality Control Maintenance & Troubleshooting	**Management** Administrative or Group Management Project Management Technical Management Planning
Technical Communication Writing and Editing Drafting and Drawing Information Search Reading	**Other Communication** Meetings and Seminars (attendance) Briefing Preparation and Presentation Education and Training
Other: Administrative activities, holiday and vacation, travel, etc.	

Table 2. A taxonomy of engineering work at two electronics firms.

TIME PROFILES OF ENGINEERING WORK.

Questionnaires were distributed at Company 1 during 1987 and 1988, and at Company 2 during 1988 (Figure 5). The returned questionnaires were aggregated by company, serial number, and year sent. Each responding engineer carries equal weight, irrespective of the number of questionnaires he or she returned in any particular year.

SURVEY OF ENGINEERING WORK AND USE OF COMPUTER TOOLS

General Instructions: Please answer *ALL THREE PARTS* of this questionnaire, *whether you used computer tools or not.* Answers should reflect work activities for TODAY ONLY. You are under no obligations to answer or return this questionnaire. If you choose to respond, all responses will be kept strictly confidential. *Study conducted by the D. Murotake and the MIT Sloan School of Management.*

PLEASE MARK TODAY'S DAY:	Monday	Tuesday	Wednesday	Thursday	Friday	Weekend

PART I - PROJECT AFFILIATION

Please identify the project(s) you worked on today. If you worked on more than two projects, list the two you worked the most on. Project Description is necessary only if you don't know the shop order.

Project Description	Shop Order	Hours	Project Leader/Manager
1.			
2.			

PART II - ACCESS TO COMPUTER TOOLS

HARDWARE TOOLS		SOFTWARE TOOLS	
1. Supercomputer (Cray)	6. PC (IBM, MAC)	1. Word proc, text editor	6. File convert, transfer
2. Mainframe (IBM 370)	7. Network, Modem	2. Drawing program	7. Data capture, analysis
3. Mini (VAX 780, uVAX)	8. Printer, Plotter	3. Spreadsheet	8. Programming tools
4. Workstation (Apollo, Sun)	9. Input Dev (Mouse)	4. EMail, BBS, Info Svc	9. CAD, CAM, CAE
5. Terminal (VT100, VT220)	0. Other Hardware	5. Terminal emulator	0. Other Software

1. Which of the hardware tools (1-0, above left) are available to you in your primary work area (where you spent most of your time)?________________

   Which of the software tools (1-0, above right) are available?____________________

   How many people share these tools with you? 0_____ 1_____ 2+_____

2. Did you use any computer tools today? YES_____ NO_____.

   (If you answered no, skip Question 3, then continue.)

3. What experience did you have today with respect to computer resource contention?

   (Examples: waiting to use a MAC or software package; slow network or VAX response.)

   _____**NO CONTENTION** No lost work, in my estimation.

   _____**MINOR CONTENTION** Less than half-hour of lost work.

   _____**MAJOR CONTENTION** More than half-hour of lost work.

4. If you used (or thought about using) computer tools today, check all boxes below that apply, and place the appropriate hardware/software codes in the space provided.

	TOOLS
a. ____ NEEDED new functionality or capability, but had no way of knowing if tool is available.	
b. ____ Knew of hardware or software which would be ideal for my work, but it was unavailable.	
c. ____ Evaluated new tool but DECIDED NOT TO ADOPT IT since it didn't meet my needs.	
d. ____ Evaluated new tool and DECIDED TO ADOPT IT for my work, at least someday.	
e. ____ I thought about using a computer tool today, but COULDN'T AFFORD TIME to learn it.	
f. ____ I spent some time LEARNING HOW TO USE NEW a new computer tool today.	

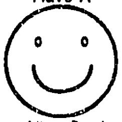
EVERYONE PLEASE DO PART III ON BACK!
(EVEN IF COMPUTER TOOLS NOT USED)

Figure 5a. Front page of the engineering work questionnaire. Each engineer in the sample population received one or two of these per month on a randomly selected work day. Stratified random sampling was used.

PART III - WORK TIME ALLOCATIONS AND COMPUTER USE

INSTRUCTIONS: Please enter the number of hours you spent TODAY in each of the task types listed below, using the column HOURS WORKED TOTAL. Enter the number of hours spent using computers (if any) in the column HOURS ... W/COMP. Show which computer hardware and software tools you employed (if any), using the appropriate codes in the columns marked COMPUTER TOOLS USED. Finally, please rate the effectiveness of the computer tools you used (compared to doing work manually) in the columns marked RATING OF COMPUTER TOOLS. Give separate ratings for productivity and quality.

Have A



Nice Day!

HARDWARE CODES
1. Supercomputer (Cray)
2. Mainframe (IBM 370)
3. Mini (VAX 780, uVAX)
4. Workstation (Apollo, Sun)
5. Terminal (VT100, VT220)
6. PC (IBM, MAC)
7. Network, Modem
8. Printer, Plotter
9. Input Dev (Mouse)
0. Other hardware

SOFTWARE CODES
1. Word proc, text editor
2. Drawing program
3. Spreadsheet
4. EMail, BBS, Info service
5. Terminal emulator
6. File conversion, transfer
7. Data capture, analysis
8. Programming tools
9. CAD, CAM, CAE
0. Other Software

COMPUTER TOOL RATING CODES
1. Not as good as manual work
2. Equivalent to manual work
3. Better than manual work
4. Impossible to do manually
5. Unsure

ENGINEERING TASK TYPE	HOURS WORKED		COMPUTER TOOLS USED		RATING OF COMPUTER TOOLS	
	TOTAL	W/COMP	HARDWARE	SOFTWARE	JOB PRODUCTIVITY	QUALITY OF WORK
ENVIRONMENT SCANNING						
Market Evaluation						
User Requirements Evaluation						
Technology Evaluation						
ANALYSIS						
Problem Identification						
Idea Generation						
Experimentation						
Mathematical Analysis						
System Modeling and Simulation						
Tradeoff Analysis						
Cost Estimation and Bidding						
SYNTHESIS						
Overall System Design & Specification						
Mechanical Design & Specification						
Electrical Design & Specification						
Software Design & Specification						
Mechanical Develop & Prototype						
Electrical Develop & Prototype						
Software Develop, Code & Debug						
Overall System Integration & Test						
PRODUCTION & MAINTENANCE						
Manufacturing (Process) Engineering						
Quality Control						
Troubleshooting & Maintenance						
COMMUNICATION						
Discussions and Meetings						
Writing and Editing						
Drafting and Drawing						
Searching for Information						
Reading						
Presentations, Demos, & Briefings						
Education & Training						
MANAGEMENT ACTIVITIES						
Project or Operations Management						
Group or Section Management						
System Management						
Planning (e.g. R&D Planning)						
						2/17/88

Figure 5b. Back page of the engineering work questionnaire. Although complex-looking, the single-page questionnaire had a higher rate of return from engineers than simpler-looking, multi-page questionnaires in pre-tests.

Time Allocations for Engineering Work

Engineers at both sites spend a significant portion of their average work day on analysis, design, and development related tasks (Figure 6). On the average, Company 1 engineers spend more time in production support and maintenance work (over one hour per day) than their Company 2 counterparts, while Company 2 engineers spend more time in analytic and management work.

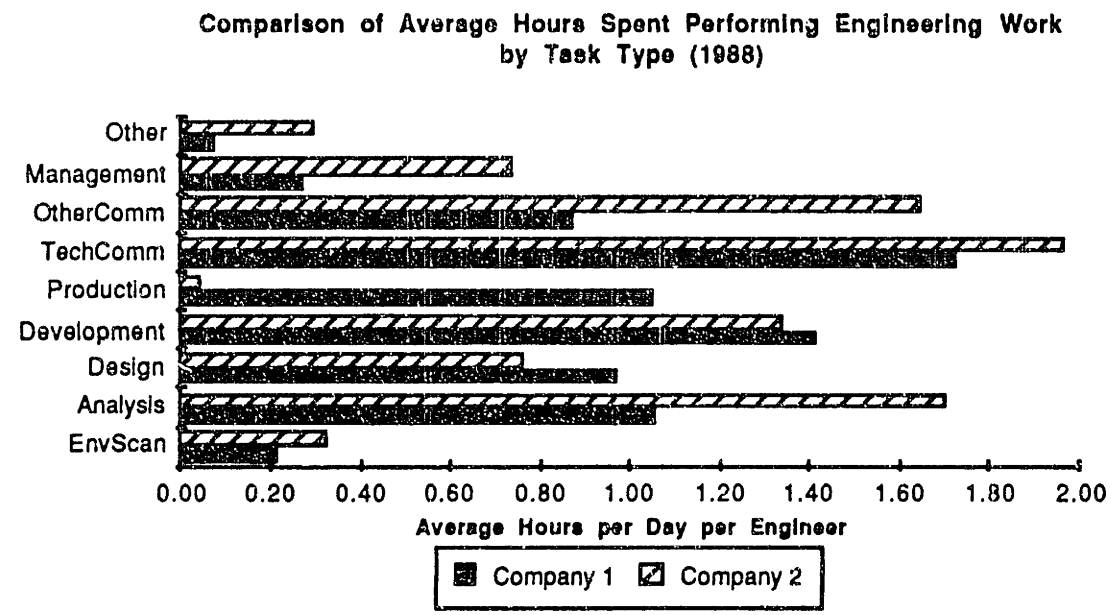


Figure 6. Average hours per day spent on engineering work by 73 engineers at two US engineering companies in 1988, based on a sample of 1,612 hours (197 man-days). Analysis, development, and technical communication tasks each took more than an hour of time per average day at both sites.

At Company 1, almost half (46%) of the average engineer's workday is spent on "traditional" engineering activities, such as analysis (14%), design (13%) and development (19%) (Figure 7). Engineers at Company 1 spend over a third of their average day engaged in some form of communication. Technical communication (drawing, writing, reading, searching for info) account for almost a quarter (23%) of the average work day, while other communications accounted for another twe! 'e percent. (Some engineers suggest that communication time is actually greater, believing their fellow engineers to be reluctant to report such "unproductive" activities.)

Despite the significant cultural differences between the two companies, one gets a sense of deja vù when looking at the time allocation data for Company 2. For instance, Company 2 engineers spend about half (45%) of their average day on "traditional" engineering activities (Analysis, 20%; Design, 9%; and Development, 16%) (Figure 7).

Like their counterparts at Company 1, Company 2 engineers spend twenty-three percent of their average work day on technical communications, although engineers at Company 2 spend more time than their counterparts at Company 1 on other communications (19% versus 12%). Thus, over forty percent of the average work day is spent communicating.

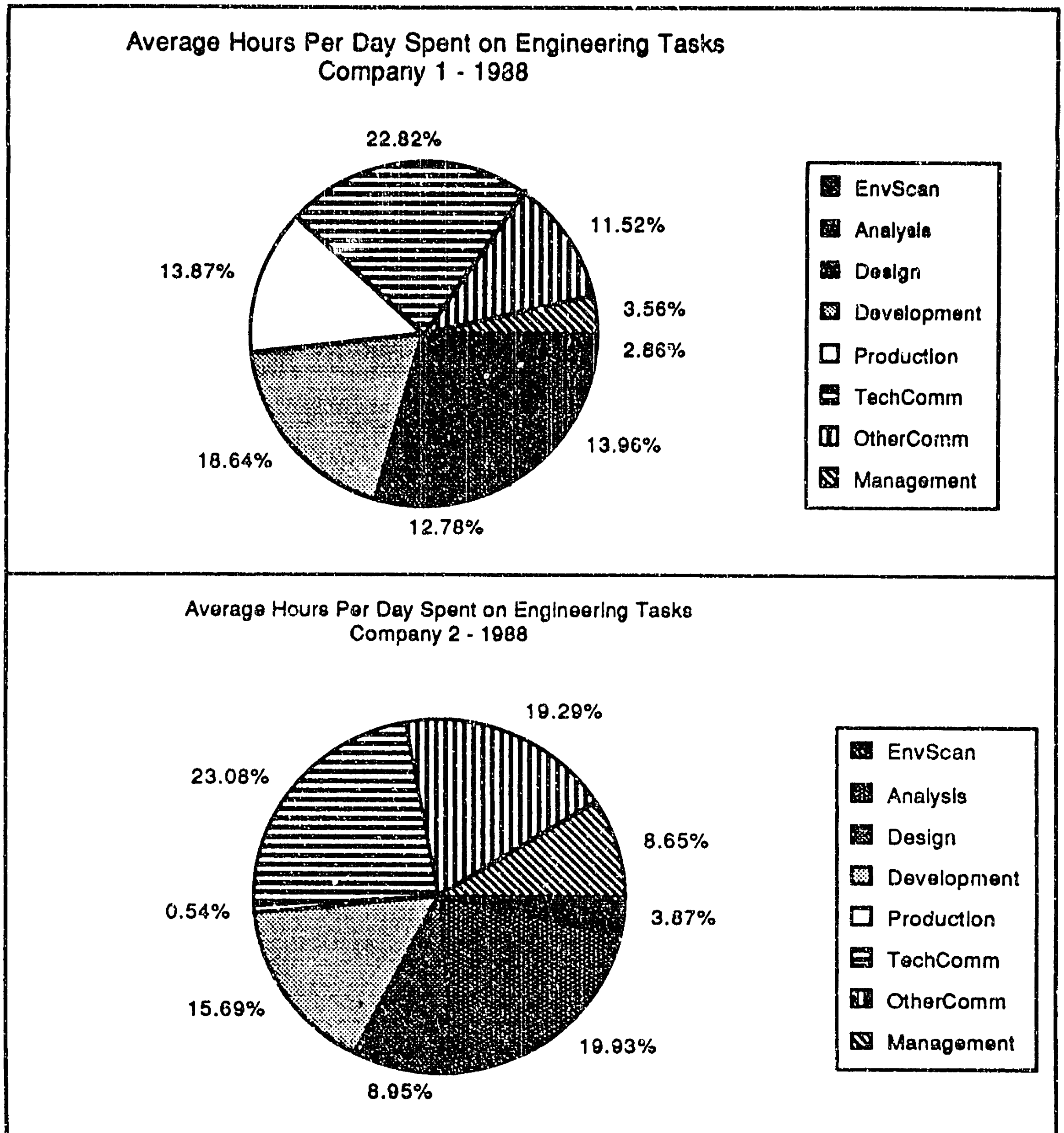


Figure 7. Average time allocation per workday for engineers at Company 1 (N=44) and Company 2 (N=29) during 1988 survey period. Note the substantial differences between these pie charts and the HP chart (Figure 3.)

Lesson learned: Engineers spend just under half their day (about 45%) at the "traditional" technical tasks of analysis, design, and development. A significant part of their day (35%-40%) is spent communicating. In particular, about 25 percent of their day is spent in technical communication and documentation.

Engineering Is a Group Activity.

Engineering projects are rarely one-man shows. Project teams, though often small (3-5 engineers) can number over fifty members. Because of the group nature of engineering work, communication requires substantial amounts of time and effort by engineers, and constitutes a major part of the engineer's average work day (Figure 7). It takes cooperative effort from several individuals, each with a different set of skills, to make up an engineering project team. Team members must communicate and cooperate; the team itself must be managed and led.

CHAPTER 3. COMPUTER TOOLS FOR ENGINEERING.

The term computer aided engineering (CAE) has been coined to describe a broad spectrum of computer hardware and software tools used by engineers. These tools range from personal computers with relatively simple, separate applications (such as word processors, drawing tools, programming language compilers, and spreadsheets), to elaborate networks of powerful workstations and mainframes with computer aided design (CAD), computer aided software engineering (CASE), data acquisition, simulation, and office automation tools.

Impressive time savings can result from the use of CAD and CAE. VLSI designs which used to take several months can now be performed in a matter of hours using silicon compilers, special CAD tools for designing chips (Wallich, 1984a). However, computer tools are like the proverbial double-edged sword. They can vastly shorten the time needed to bring new products to market, while simultaneously lowering their cost, speeding up their delivery, improving their quality and stimulating more innovation in their design. But they can also inadvertently damage on the backstroke. Increased homogeneity of designs can result in less innovative, or even suboptimal, design solutions. Skilled labor can be misutilized to perform inappropriate tasks. Time can be lost due to system crashes, resource contention, or low system performance. Inadequate user training can adversely affect a firm's profitability and competitiveness. Reduction in job skill requirements based on job automation can cause boredom and job dissatisfaction, while increases in production efficiency can displace jobs.

In this chapter, we begin by reviewing some literature on computer aided work. We examine the use of computer tools by engineers, and how this use varies as a function of the capability of available tools, using data from field work done at the two research sites.

LITERATURE REVIEW.

Computer Tools for Engineers

In Chapter 2, we discovered the "traditional" technical work of engineering constitutes less than half of the engineer's work day, with significant amounts of time spent in communication and normal office routine. Some industry spokesmen recommend improvements in engineering productivity by attacking the administrative overhead with office automation tools. To support the full range of engineering work, computer tools for engineers should address all major components of engineering work: mathematical analysis, engineering design and development, desktop publishing, and technical communication. This integration of diverse tools in a workstation toolkit is one of the major thrusts of CAE development:

> CAE is an outgrowth of CAD and design automation... CAE brings the computer into the design process further upstream - from the physical aspects of the design to the design itself. Using CAE, the modern engineer can conceive, design, simulate, modify, and draft at a single workstation. (Swerling, 1982)

Evolution of Computer Tools

The evolution of a firm's CAD/CAE system is an ongoing, evolutionary process, with new hardware and software tools being constantly introduced, evaluated and (if adopted) added to the existing suite of computer tools. Because of their cost-effectiveness and relatively low entry costs, CAE systems based on personal computers (such as the IBM PC® and Apple Macinstosh©) and entry-level engineering workstations are becoming commonplace within the industry. But the "solution" has opened up a Pandora's box of standardization issues. Incompatibility seems to exist at every level. Software applications are incompatible with other applications; computers are often incompatible with other types of computers; and solutions well-suited to individual contributors are often ill-suited to the needs of organizations.

New industry standards, such as EDIF (Electronic Data Interchange Format) promise to revolutionize CAE by making standard data interchange formats available for porting text, graphics, and design data between different engineering design and office automation tools (Alward, 1987). This will allow CAE hardware and software from many different vendors to work more easily together. As new computer tools are adopted, CAE systems and other "electronic hierarchies" gradually evolve from systems with separate applications and databases, to systems with linked applications and databases, finally moving to fully networked systems with shared applications and databases (Malone, 1987). CAE system development has been moving steadily in the direction of linked and shared design data bases (Schuler et al, 1987) (Figure 8).

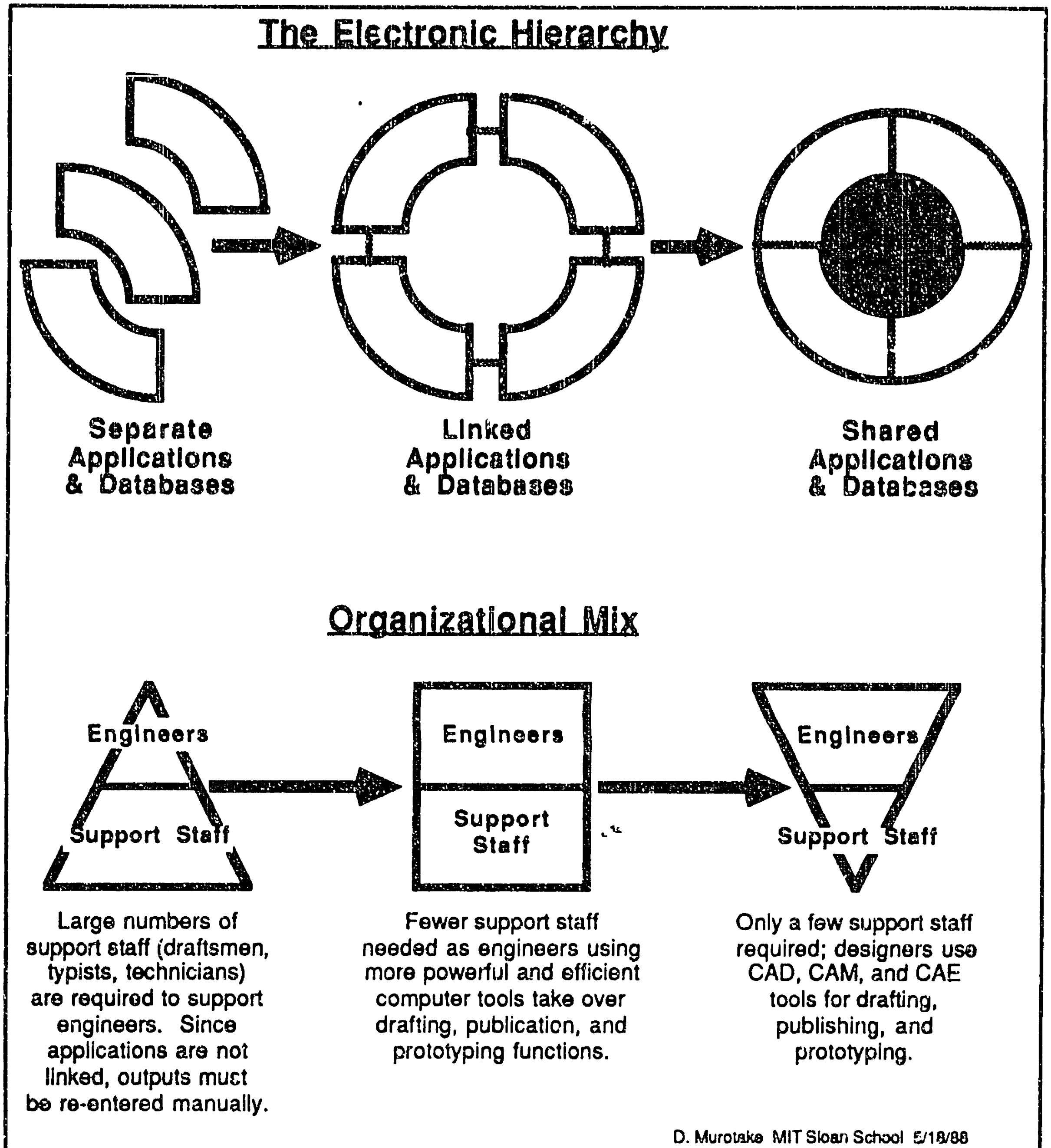


Figure 8. Evolution of computer tool environments. Shifts in organizational hierarchy should be matched by appropriate shifts in the electronic hierarchy, or chaos may result. (Electronic hierarchy from Malone, 1987. Organizational mix from unpublished Company 2 internal study, 1988.)

Today, the "norm" for CAE appears to be an environment centered on personal computers of modest performance, loosely networked with other PC's, workstations, minicomputers, and mainframes. The PC's are used for technical, business, and management purposes (McDermott, 1984; Miller & Kelley, 1984; Stern & Voto, 1986). Software applications (and their data bases) are generally separate, with some "linking" of these applications and data bases through the use of "translator" utility software. Company 1 fits this category.

Some firms are more heavily automated, with large numbers of high-performance engineering workstations clustered in cooperative networks with other computing resources such as mainframes and supercomputers, high-capacity file servers, and print servers. In these systems, software applications (and their data bases) are generally linked. Different CAD/CAM applications from various vendors share a common data base for design information (Schuler et al, 1987). Company 2 fits this category.

As the tools grow in capability, engineering firms may take advantage of the efficiencies of the automation system by altering the organization mix, reducing the percentage of support staff. In an unpublished internal study, Company 2 claimed that halving their engineering support staff over several years was accomplished with no apparent loss of quality or capability. In fact, such staff reductions are often cited as cost justifications for the procurement of new automation systems (Chasen, 1980; Appendix C).

Factors Influencing the Use of Computer Tools.

Factors influencing the use of computer tools can be put into two categories: motivators towards use, and barriers to use. Perceptions of usefulness are behavioral motivations to use the tool, and should stimulate increased use of these tools in a motivational model (Szilagyi & Wallace, 1980; Leavitt, 1972).

A study of technology acceptance by Davis (1985) showed perceived utility to be the single most important factor among those tested to be correlated with the use of new computer tools . A study of 112 software engineers, system analysts, and managers at IBM-Toronto showed that perceived utility influenced both attitudes towards the use of electronic mail and editors, as well as the actual frequency of use of these tools (Figure 9).

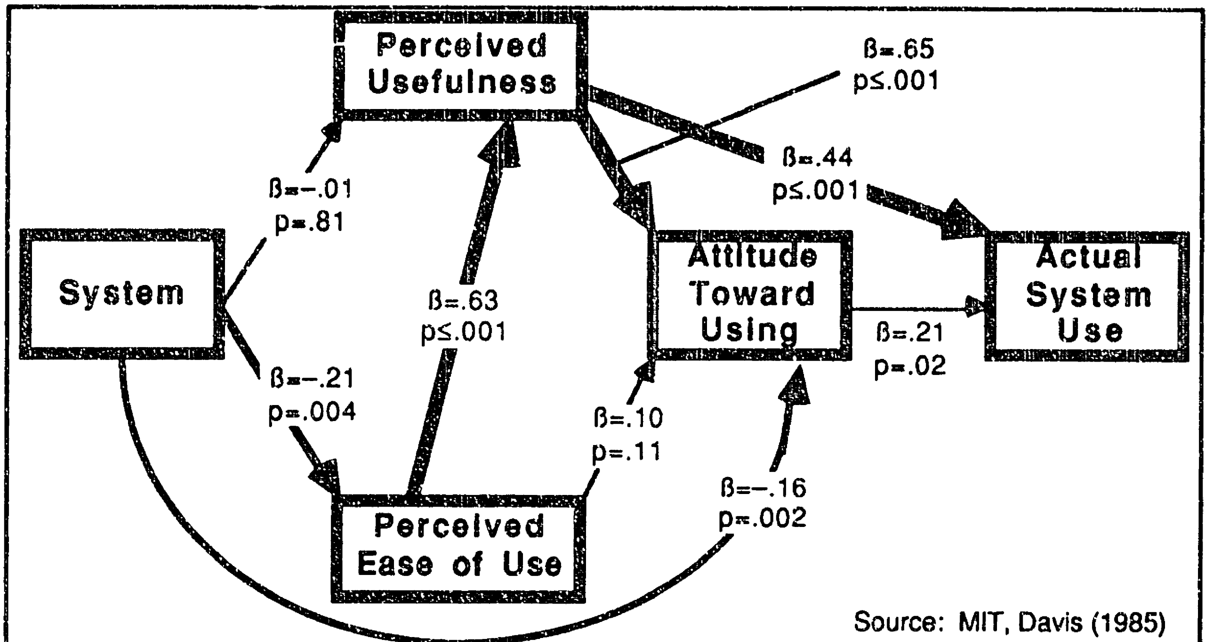


Figure 9. Technology acceptance model proposed by Davis (1985). In this regression analysis of technology acceptance, strong and significant causal links were established between perceived usefulness and BOTH attitude toward using a new computer tool , and actual use of the tool.

On the other hand, contention for resources, lack of accessibility, and reluctance to use unfamiliar or unfriendly tools are examples of barriers to use. For instance, accessibility of communication channels is strongly correlated with the frequency of their use (Kendall τ=.67, N=19, p<.01; Gerstberger & Allen, 1968).

Changing the Nature of Work - Sociotechnical Implications.

Computer tools, because of their power, have profound sociotechnical implications, changing the very nature of work and the quality of working life. Some of these changes can be beneficial, and others can be detrimental.

The engineer of tomorrow is... a machine? CAE tools are increasingly relying on AI and expert systems technology. Some industry observers predict that many of today's professionals with highly specialized skills, including engineers, medical specialists, bankers, and stockbrokers, will be replaced by expert machines within the next century (Hayes-Roth, 1984; Garson, 1988). The surviving "engineer of tomorrow" will probably be a system engineer, an all-can-do generalist capable of going from "birth to grave" in the customer interface, analysis, design, development , manufacture and documentation of new products and processes (with the help of the trusty computerized sidekick, the workstation). Indeed, modern CAD/CAM systems are already beginning to approach this capability, in industries ranging from semiconductor chips (Wallich, 1984a) to jet engines (Shaiken, 1984).

I can do it all myself. The rest of you can get laid off. In the near term, as computer tools become more powerful, the number of support staff (draftsmen, consultants, etc.) can be reduced as computer tools permit engineers to do ever increasing portions of the work themselves (Swerling, 1982). This process is already well advanced in the engineering industry, as draftsmen, technicians, and secretaries fall victim to the ever-expanding capabilities of the new machine, working as a team-mate of today's engineer. In this fashion, skilled manpower can be leveraged using computer tools (Chasen, 1980; Shaiken, 1984). This ability to "do it all myself" is often welcomed by the engineer, as it offers freedom from the frustrations of waiting for other workers, and editing their mistakes (McDermott, 1984). But this same increase in efficiency can displace jobs. Reduction in job skill requirements because of automation can also displace jobs for skilled workers, and result in expanded work for those remaining in the workforce (Shaiken, 1984).

Work at home. Have workstation, will travel. Designs by the piece. Growing use of computer workstations, electronic communications (EMail, VoiceMail) and portable computers may soon "liberate" many engineers from the traditional workplace. The office of tomorrow, thanks to the computer, may be at home (Trist, 1981). Today's engineer often works away from the lab, using a PC and modem at home, or a "laptop" portable while travelling or in the field, as a "virtual office." Tomorrow's engineers may do much of their work on portable workstations which move with them from site to site, and from job to job. This could open up engineering opportunities to those currently unable to pursue this profession due to physical or other constraints (senior citizens, single parents, etc.). Liberating the engineer from the workplace can improve the quality of working life and improve productivity (Seashore, 1981). Working at home may also affect the way in which engineers are compensated in the future. "Piece rates" may replace salaries, effectively turning the white collar work force of today into the blue collar work force of tomorrow (Garson, 1988).

The electronic sweatshop. The computerized R&D laboratory of the future may be nothing more than an electronic sweatshop, with today's skilled white-collar engineers replaced by blue-collar technicians operating intelligent machines (Shaiken, 1984; Garson, 1988). Actual or perceived performance monitoring of computer work can result in high stress. In a study of information workers using workstations, the stress was the highest recorded by NIOSH, exceeding that of air traffic controllers (Schlefer, 1983). Extensive use of computer tools in engineering may result in boredom, alienation from the job, and dissatisfaction (Walters, 1974). This degradation of quality of working life should be a concern to both management and worker alike, as these are all factors poised to erode the potential productivity gains resulting from improved tools (Seashore, 1981).

HYPOTHESIS.

Hypothesis 1: Given access to computer tools in the immediate work area, *computer tools are used more by engineers when more sophisticated tools are available.*

The hypothesis attempts to establish a relationship between the sophistication of available tools, and the use of those tools by engineers. This hypothesis would corroborate the strong correlation between perceived utility and the use of electronic mail and editing tools by engineers (Davis, 1985), and the strong correlation between accessibility and use of information channels (Gerstberger & Allen, 1968).

To show that the hypothesis is true, we will:

-Show the extent to which engineers use computer tools to support their work, and the availability of hardware and software tools.

-Form an ordinal "capability" measure for computer tools available in the engineer's immediate work area (No capability, Basic Office Automation, Limited Technical capability, Advanced Technical Capability), assuming the highest utility for "advanced technical capability", and the lowest utility for "no capability."

-Aggregate the engineering work and computer use data by project. Purpose: Shift the unit of analysis from individual engineer to project.

-Compute the correlation coefficients between computer use and various project characteristics. Purpose: Identify intervening variables for partial correlation.

-Demonstrate that the availability of computer tools is the dominant source of variation when controlling for the intervening variables.

ENGINEERING COMPUTER USE.

(Note: Data shown in this section are aggregated *by engineer*. Questionnaires returned by each engineer are averaged to show one man-day of work.)

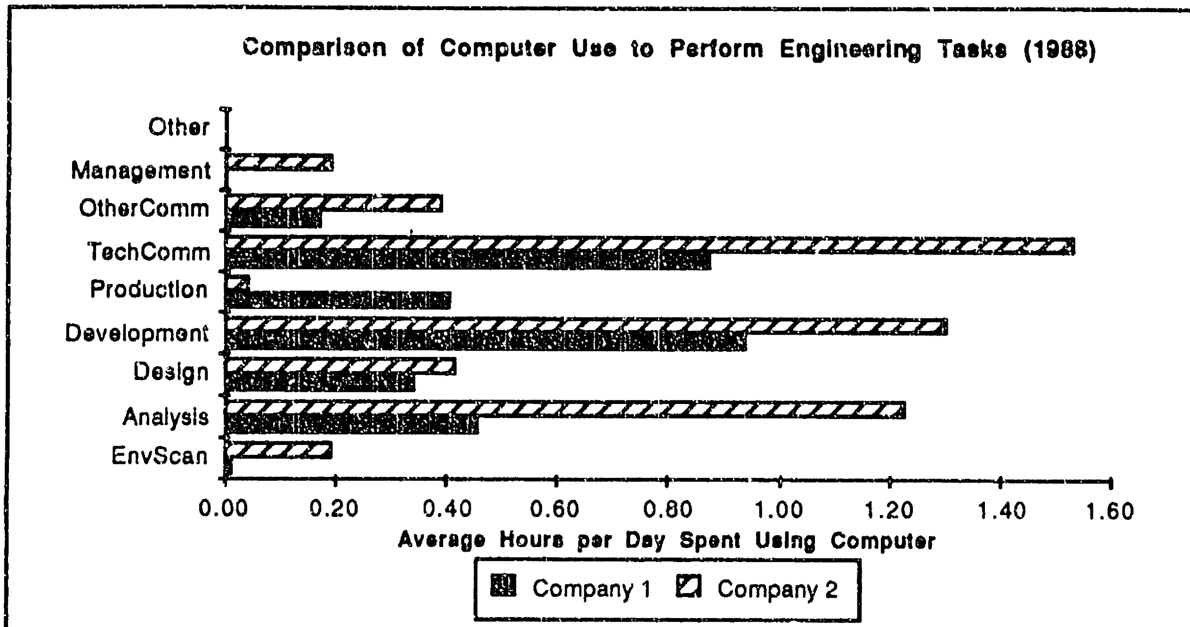


Figure 10. Average hours per day engineers spent in using computers to support their work, based on a 1988 sample of 1,612 hours of work at two US engineering companies. Engineers at Company 1 use computers 3.2 hours per day (42% of work day), while their Company 2 counterparts use computers about 5.4 hours per day (60% of work day).

Most of the computer time (55%) reported by Company 1 engineers is in traditional engineering activities, such as analysis (16%), design (13%), and development (25%). Over a quarter of the computer time (27%; 30% including environment scanning) is in communications-related activities (Figure 11).

By comparison, Company 2 engineers spend less than half (44%) of their computer time on the "traditional" engineering task categories of analysis, design, and development (Figure 11). Thirty-one percent of computer time is spent supporting communication-related activities. Note that environment scanning activities account for twelve percent of Company 2's computer use - quadruple that spent by Company 1 engineers.

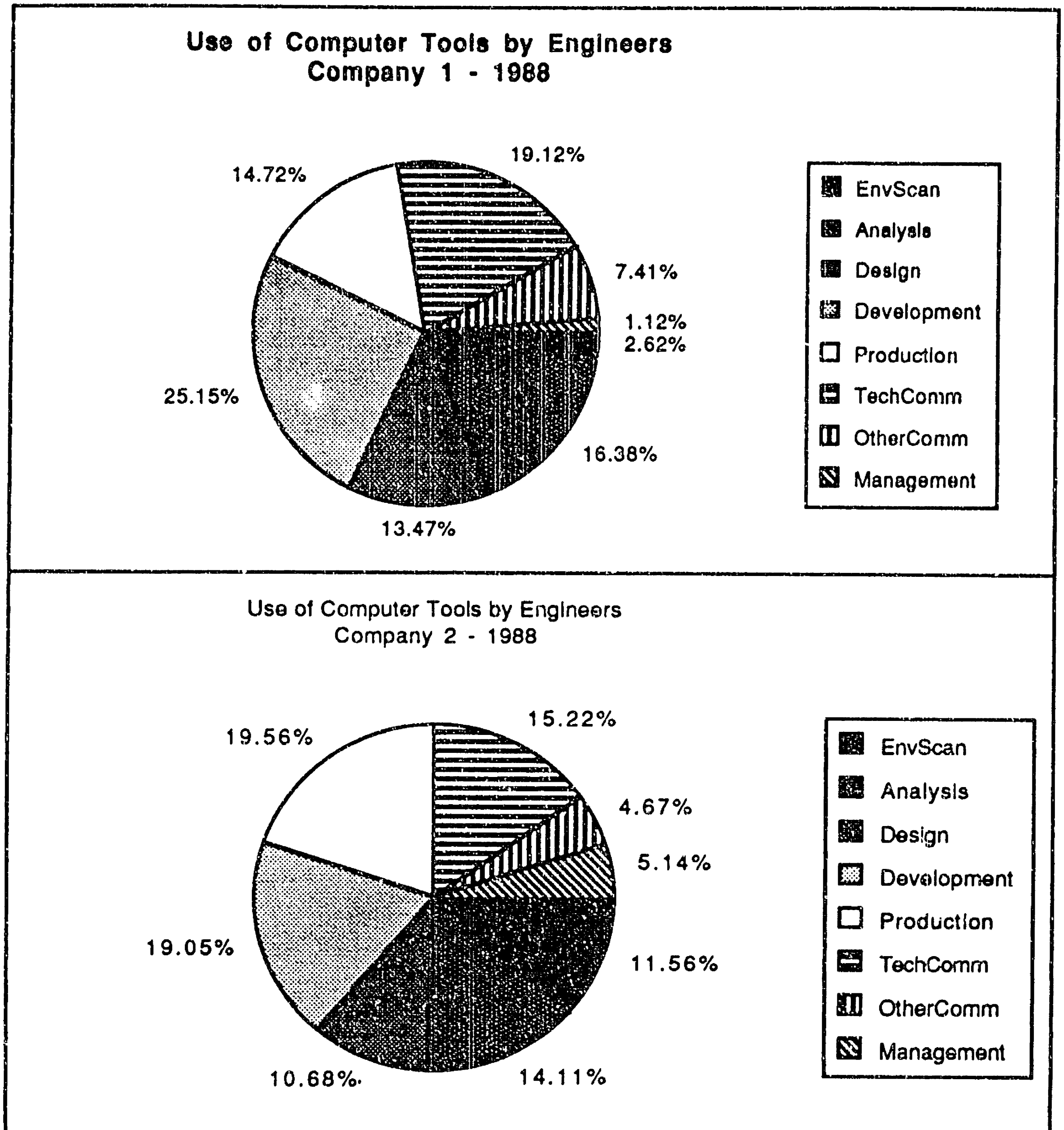


Figure 11. Pie charts showing computer time allocations at the two research sites during 1988. "Traditional" engineering tasks of analysis, design, and development account for approximately half the computer time used at both sites, while communication related activities (Tech Comm, Other Comm, and Environment Scanning) account for approximately 30% of computer time. Data is aggregated by engineer, and represents an average of 1988 samples.

Computer use varies considerably across different categories of engineering activity at both sites. Analysis, design, development, production support and technical communication work are all computer-intensive tasks, with over 35 percent of the hours worked on them being spent at the computer.

Engineers at Company 2 spend a higher proportion of their work time using computers than Company 1 engineers. (Note: This is not a surprising result. First, two-thirds of the respondents at Company 2 are software engineers. Second, the ubiquitous workstation and "paperless office" environment result in increased use of computers, including the sending of interoffice memos, and the lookup of telephone numbers.) Almost all of the time spent doing production support, development, and technical communications are with the computer. Most of the time spent on environmental scanning, analysis, and design are also spent with the computer. (Note: An online marketing research "clipping service" on new technologies and competitor activities is available at Company 2, and is accessible by all engineers. By contrast, such information is usually restricted to marketing and management personnel at Company 1, and is usually provided in printed form.)

Lesson learned: Engineers use computers to perform a wide range of engineering work. About half of the engineering use of computers supports traditional technical activities such as analysis, design, and development. About a fourth of the computer time is spent on technical documentation and communication related work.

Hardware Tools - Availability and Use.

The proportion of engineers reporting the availability of nearby hardware tools is plotted versus the proportion of engineers reporting their use in Figure 12. In general, computer tool use is positively correlated with their availability.

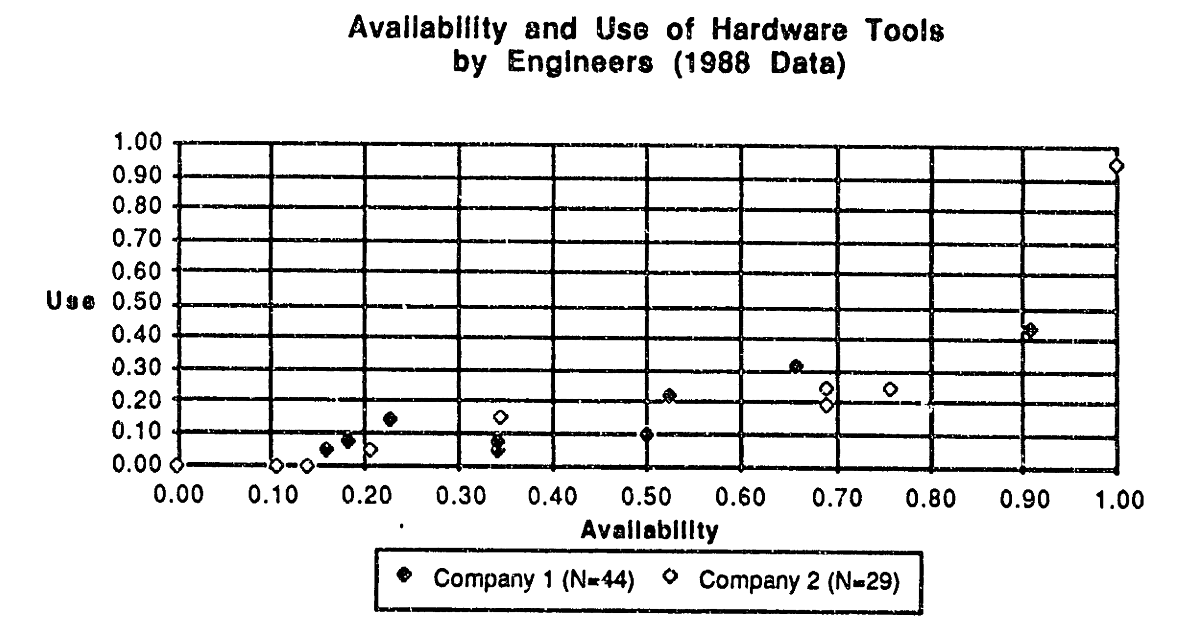


Figure 12. Scatterplot of use vs availability of computer hardware tools in the work area. Each data point represents the percentage of engineers using a specific hardware tool (e.g. PC's, engineering workstations, printers) as a function of its reported availability at each company.

At Company 1, over 90 percent of the engineers report the availability of nearby computer terminals. (Note: These terminals are connected via terminal servers and local area network to one or more minicomputers.) Similarly, about two-thirds report availability of personal computers. About half of the engineers with access to terminals and PC's use them.

At Company 2, all engineers report the availability of nearby engineering workstations, while 95 percent report their use. (Note: Company 2's policy is *one engineer, one workstation*.) Workstations are usually connected via local area network to other computing resources (Appendix B). Availability of PC's at Company 2 is low (20%), and their utilization is lower still (5%). Mainframes, minicomputers, and terminals are not used. The personal engineering workstation takes the place of the PC for engineers at Company 2.

Software Tools - Availability and Use.

The availability and use of software tools for engineering work is extensive at both sites, although more so at Company 2. In general, the use of computer software tools increases with increasing availability. Noteworthy is the widespread use of editors and word processors at both sites, and the near-universal use of editors and electronic mail at Company 2 (Figure 13).

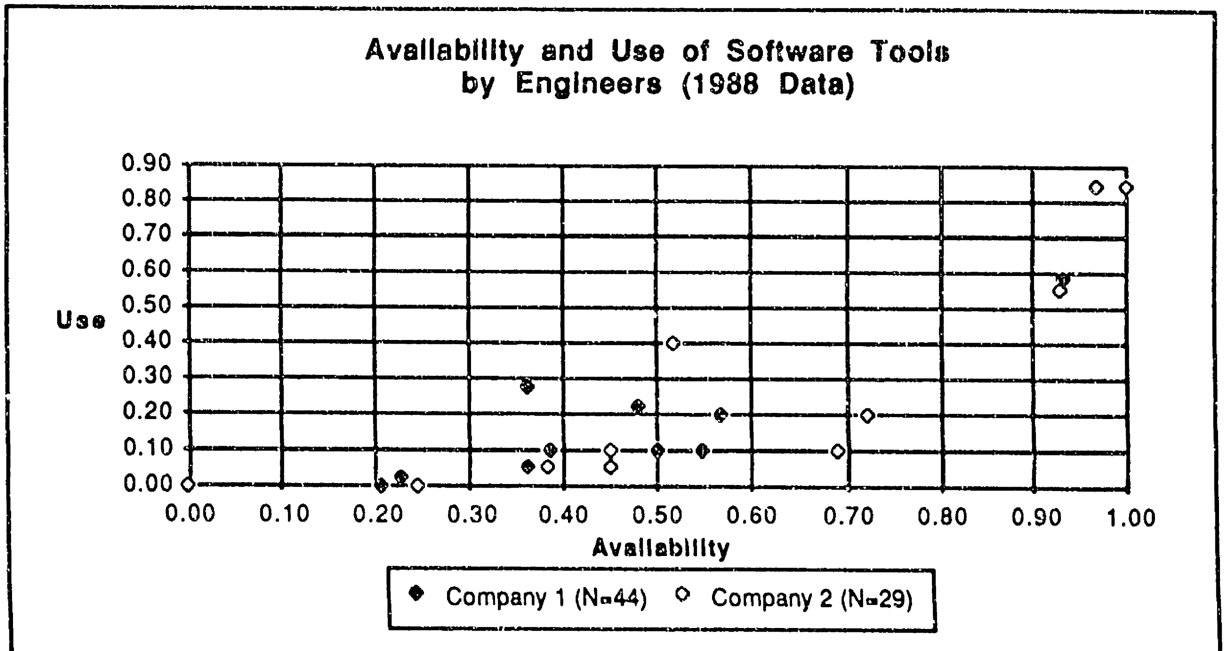


Figure 13. Scatterplot of use vs availability of computer software tools in the work area. Each data point represents the percentage of engineers using a specific software tool (e.g. programming tools, computer aided drafting, word processors) as a function of its reported availability at each company.

Over ninety percent of engineers at Company 1 report the availability of word processors or text editors, while nearly sixty percent use this most popular software tool. Though most engineers also report the availability of drawing tools, electronic mail, and spreadsheets, only a few use them. In particular, of the fifty-five percent with access to electronic mail, only ten percent used it (Figure 13). By contrast, electronic mail is available to all engineers at Company 2, and used by eighty-five percent. (Note: Widespread availability of certain types of tools is in part due to site licensed software for PC's. The software, which is freely distributed and used throughout the company, includes a word processor, data base, spreadsheet, and mathematical analysis software. Similar software is available on the network-accessible minicomputers.)

A rich selection of software tools is available at Company 2. Word processors, text editors, and electronic mail are available to all engineers, and almost all use them (Figure 13). (Note: The workstation is a central part of Company 2's technical culture, and the gateway into their "paperless office"; Appendix B.1.) Programming tools are available to the vast majority; most of the engineers use them. (Recall that most engineers in the sample are software engineers.) Most engineers also report the availability of drawing tools and file transfer utilities, while nearly half report the availability of CAD/CAM tools and spreadsheets. Eighty-five percent of the engineers used word processors and electronic mail, while over half employed programming tools during the test period.

The Sophistication of Available Computer Tools.

To simplify the vast array of available hardware and software tools at the two companies, the tools have been classified into four categories:

No tools available: No computer hardware or software tools are available to engineers in the project team in their immediate work area.

Basic Office Automation: The only tools immediately available to engineers in the project team are basic office automation tools such as editors, word processors, painting/drawing tools, mainframe/network access, and electronic mail. Hardware is generally a personal computer or video terminal.

Limited technical capability: Some computer tools are immediately available to engineers in the project team which can be used to aid them in technical work. In general, these tools are not integrated, and include math/statistics packages, programming tools, and advanced spreadsheets. Hardware is generally a personal computer, video terminal or workstation.

Advanced technical capability: Many powerful computer tools are immediately available to engineers in the project team. These tools are generally integrated (allowing the easy flow of outputs from one application as inputs to another), and include computer aided software engineering (CASE) tools, computer aided design and drafting (CADD) tools, and advanced simulation tools. Hardware is generally a network of advanced personal computers or workstations with access to mainframes or distributed processing.

More projects at Company 2 (55%) have access to computer tools of advanced technical capability than at Company 1 (29%) (Table 3 and Figure 14).

Table 3. Project Characteristic:Capability of Computer Tools Available to the Project's Engineers

	Company 1		Company 2	
Capability Level	**Projects**	**% of Projects**	**Projects**	**% of Projects**
No Tools Available	0	0%	0	0%
Basic Office Automation	3	14%	0	0%
Limited Tech Capability	12	57%	5	45%
Advanced Tech Capability	6	29%	6	55%
TOTAL	21	100%	11	100%

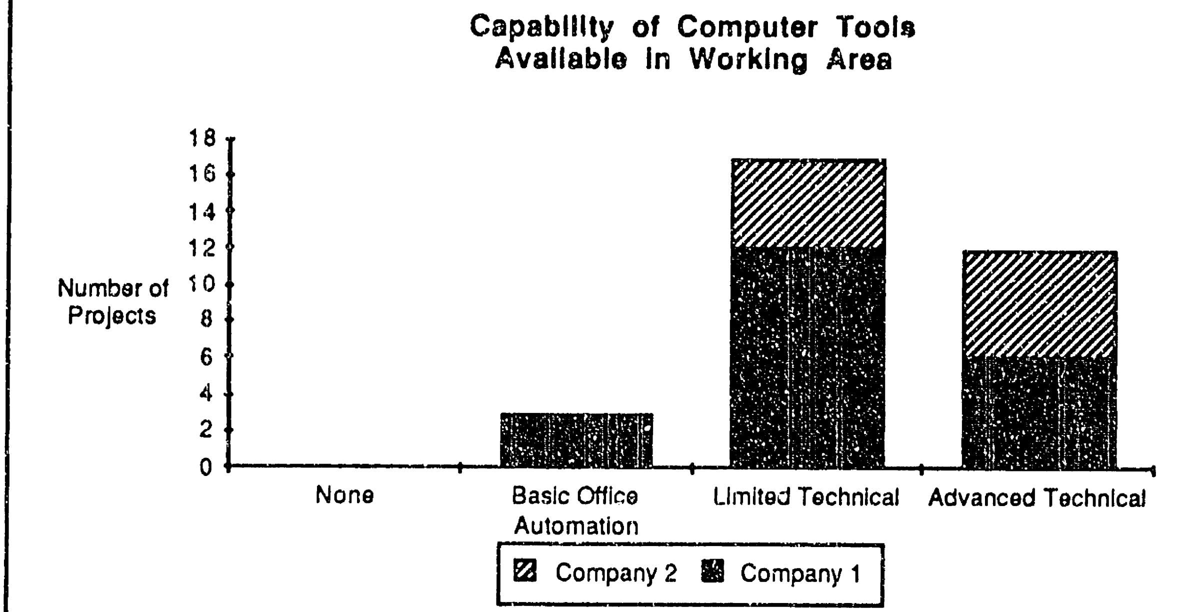


Figure 14. At both companies, project teams have access to computer tools with advanced technical capabilities including computer aided analysis, design, engineering, and drafting. However, while most (55%) project engineers at Company 2 have access to advanced tools, only a few (29%) at Company 1 have similar access.

Correlations between Computer Use and Project Characteristics.

The use of computer tools at the project level is correlated with a number of different project characteristics (Table 4). For instance, computer tools tend to be used more in smaller projects ($r = -0.36$) and at Company 2 ($r = 0.35$). Engineers at Company 1 tended to use computers less ($r=0.35$) than projects at Company 2.

Table 4. Correlation Matrix (Project Characteristics; Pearson's r, Project n=32)								
FACTOR	Soph Tools	Proj Size	Tech Soph	Proj Phase	Proj Man'g	Engr Workld	Comp Use %	Com-pany
Sophistication of Available Tools	1.00							
Project Size	-0.20	1.00						
Technical Sophistication Reqd	-0.08	0.12	1.00					
Current Phase of Project	0.09	-0.06	**-0.47**	1.00				
Project Manning Level	0.21	0.09	0.06	0.08	1.00			
Workload of Engrs in Project	-0.17	0.13	0.20	0.07	-0.01	1.00		
Comp Use (% of Overall Time)	**0.52**	**-0.36**	-0.05	0.09	0.19	0.11	1.00	
Company	0.25	**-0.32**	0.18	0.10	0.11	0.20	**0.35**	1.00

Correlation coefficients r for project characteristics. Bold coefficients significant at the 5% (two-tailed) level ($r_{.10} = \pm 0.30$, $r_{.05} = \pm 0.35$, $r_{.01} = \pm 0.45$; sample n=32).

However, the most substantial correlation (r = 0.52) is between the use of computer tools, and the sophistication of available tools (Table 4). The effect of controlling for this factor on computer use is dramatic. For instance, engineers use computers much more at Company 2 than at Company 1 (Figure 15). Given Company 2's "one engineer, one workstation" credo and their rich tools environment, this comes as no surprise.

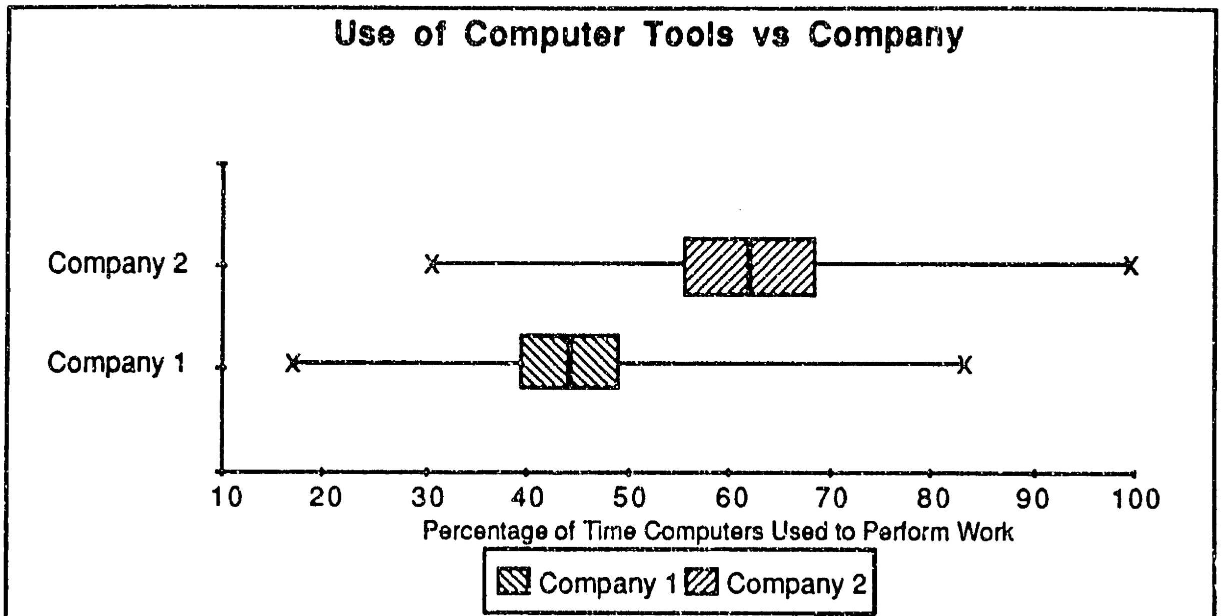


Figure 15. Box-and-whisker plot of the percentage of time computers are used to support engineering work at Company 1 (n=21, mean=44.52, SD=4.78) and at Company 2 (n=11, mean=61.09, SD=6.61). 1988 data.

Clearly, the sophistication of available tools is the dominant source of variation in computer use; by controlling for the it, company differences lose statistical significance (Table 5).

Response Variable	Source of Variation	Sum Square	DOF	Mean Square	F-Ratio	Prob (>F)
Overall Computer Use	Main Effects	7334.32	8	916.79	2.73	0.05
	Sophistication of Available Tools	2922.99	1	2922.99	**8.72**	**0.01**
	Project Size	1581.06	4	395.27	1.18	0.36
	Contention	911.44	2	455.72	1.36	0.29
	Company	181.66	1	181.66	0.54	0.48
	2-Factor Interact	4373.26	9	485.92	1.45	0.26
	Residual	4693.89	14	335.28		
	Total (Corr.)	16401.47	31			

Table 5. The sophistication of available tools is the most significant source of variation in the percentage of overall engineering work time spent using the computer. Project size, resource contention, company, and other factors are dwarfed as sources of variation. (1988 data collected at two different US engineering firms. Limited Technical and Basic Office Automation combined.)

By controlling for the sophistication of available tools, the use of computer tools by engineers at both companies assume much greater similiarity (Figure 16).

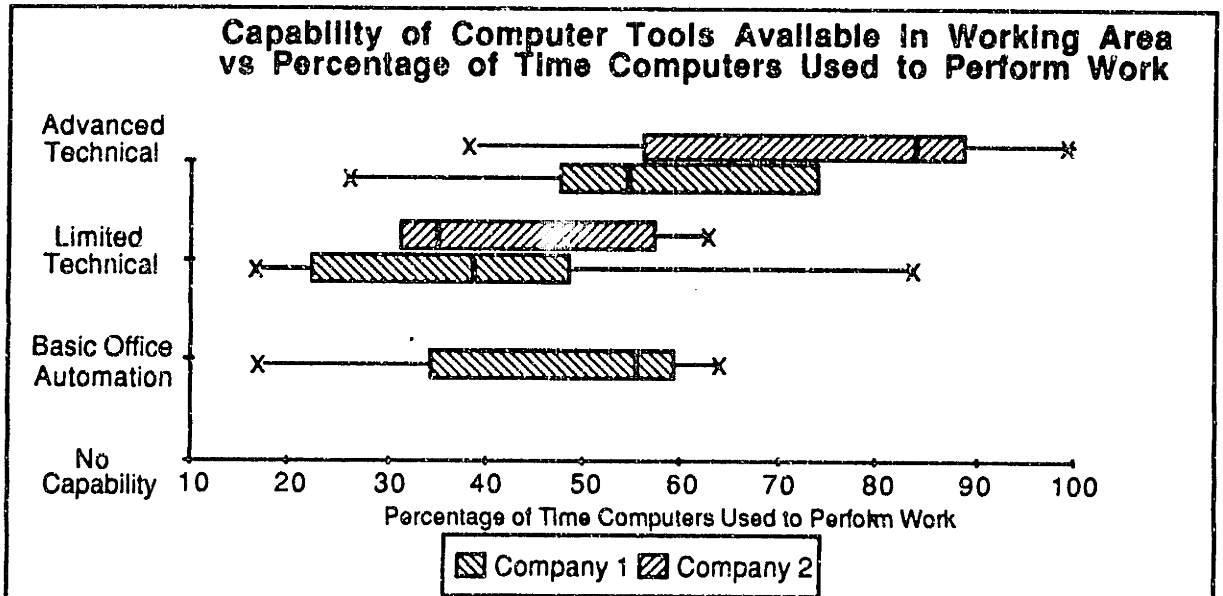


Figure 16. By controlling for the sophistication of available computer tools, substantial overlaps result in the interquartile zones for the percentage of time engineers use computer tools in their work. In the cases where limited and advanced technical capability is available, computer use increases as the sophistication of available tools increases. (Company 1 projects: n=21. Company 2 projects: n=11. Max, min, median, interquartile value shown.)

Correlation Between Computer Use and Sophistication of Available Tools.

Except for the percentage of time spent using computers for development work, there are substantial positive correlations between computer use and the sophistication of available tools in the work area (Table 6). There is an especially strong and positive relationship between the sophistication of available tools, and the use of computers for engineering design work.

Table 6. Correlation Coefficients: Computer Use vs Sophistication of Available Tools, by Task Type.					
	Overall	Analysis	Design	Develop	Comm
Sophistication of Avail Tools	**0.52**	**0.40**	**0.60**	0.00	**0.40**
Correlation coefficients **r** for project characteristics. Bold coefficients significant at the 5% (two-tailed) level ($r_{.10} = \pm0.30$, $r_{.05} = \pm0.35$, $r_{.01} = \pm0.45$; sample n=32).					

Computer use for development work is insensitive to the sophistication of available tools because development related work at both companies must be performed using computers, using specified hardware and software tools. Thus, engineers would use the needed computer tools irrespective of its convenient availability. (Note: Although the tools are available somewhere in the building, they may not originally be in the engineer's immediate work area. If the engineer spends a lot of time doing development work, either the engineer moves to the computer, or the computer is moved to the work area.)

The data **support Hypothesis 1** except in the case of development related work, in which choice of tools is constrained to the use of specific computer tools such as CASE tools, compilers, etc.

Computer Tool Selection and Use

How does an engineer decide whether or not to use a computer tool? Since real-world engineers do not normally live in work environments with unlimited hardware and software availability, a model for selection and use of computer tools should account for both constrained and unconstrained tool selection. In the case of constrained selection, a need to use specific computer tools (a DoD-approved ADA compiler), combined with a limited choice of tools (only on the VAX-6300 in the software lab), drives the selection and use of computer tools, despite restrictions to use and limitations to perceived usefulness. In the case of unconstrained selection (which drawing tool?), the user can freely select from a wider array of tools (the pencil, the Mac, the PC, or the Applicon?), and makes a rational choice maximizing both convenience and utility subject to intervening effects imposed by motivational variables, and barriers to use (Figure 17).

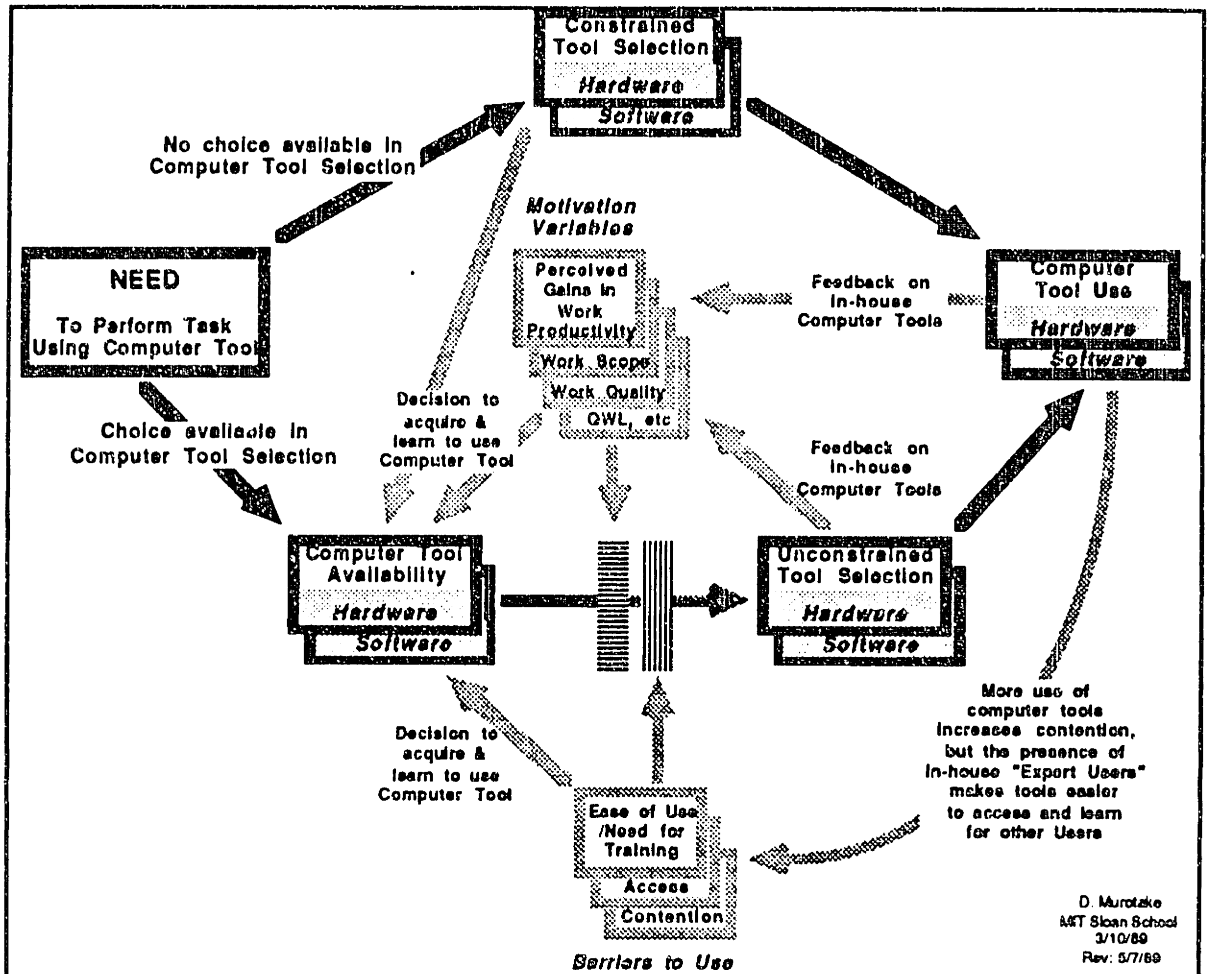


Figure 17. A model of computer tool selection. Given a choice of tools, rational users maximize convenience and utility. However, where selection is constrained by limited choice, the needed tools will be selected, acquired, and used even if such use is inconvenient or otherwise undesirable (e.g. negative impacts on quality of working life, unfriendly user interface, etc.).

CHAPTER 4. ENGINEERING PROJECT TEAMS

The design and development of complex technical products are usually performed by project teams cooperating to achieve common technical objectives (Marples, 1961; Allen, 1966a). In this chapter, we examine the characteristics of engineering project teams, and the performance of these teams with respect to the innovativeness of work, quality of work, schedule performance, and budget performance.

In our study of project teams, we shift our **unit of analysis** from that of the individual engineer, to that of the project. We do this for several reasons. First, a key research objective is to determine the relationship (if one exists) between computer use and engineering performance. Performance evaluation of individual engineers is highly sensitive personal information; neither company feels at liberty to release such information for the purposes of this study. However, both companies are willing to evaluate the performance of project teams. Research access was gained to thirty-two projects, twenty-one from Company 1, and eleven from Company 2.

PROJECT CHARACTERISTICS

A number of factors affect computer use and performance at the project level. These factors include:

- the hardware and software tools available to the engineer;
- the number of engineers involved in the project (project size);
- the level of technical sophistication required for a successful project;

– the current phase of the project in its life cycle;

– the staffing level of the project against its plan;

– the workload of engineers working on the project.

Project Characteristics Data. Data from the thirty-two projects were collected using the **Engineering Project Management Questionnaire** (Figure 18). The questions and format of the questionnaire were worked out with the participation of engineering managers at the two field sites.

ENGINEERING PROJECT MANAGEMENT QUESTIONNAIRE

You have been identified as a manager for the following project by engineers participating in a MIT Sloan School survey of engineering work & computer tools:

Mailing Label Here (Project #)

Please answer **both** parts of this questionnaire. You are under no obligation to answer it. There is no shop order for time spent in filling out this questionnaire.

I. PROJECT CHARACTERISTICS

1. **SIZE** How many people are currently involved in this project?

   1-5 6-10 11-20 21-50 51+

2. **FUNDING** What is the source of the project's funding?

   Research & Development Company funds Production Contract Other

3. **DURATION** When did this project begin? Month Year

4. **TECHNOLOGY** Please indicate the technology requirements for successful project completion. Technology can include both products (such as H/W or S/W) and processes (such as an engineering methodology or a manufacturing process).

   a. This project requires only that technology which we already had in-house.

   b. This project requires technology which we didn't originally have in-house,but which we can procure on-the-shelf from a vendor, another division or corporate lab, etc.

   c. This project requires the development of new technology - that is, technology which we don't have in-house, and which we are unable to procure from another source. (This category also covers reverse engineering of products or processes.)

5. **PHASE** What is the current project phase? (Please circle current phase.)

   IR&D Proposal Prelim Des/Devel Full-Scale Develop Production Maint & Prod Impr

6. **MANNING** What is the manning status of your project? Understaffed. Fully staffed.

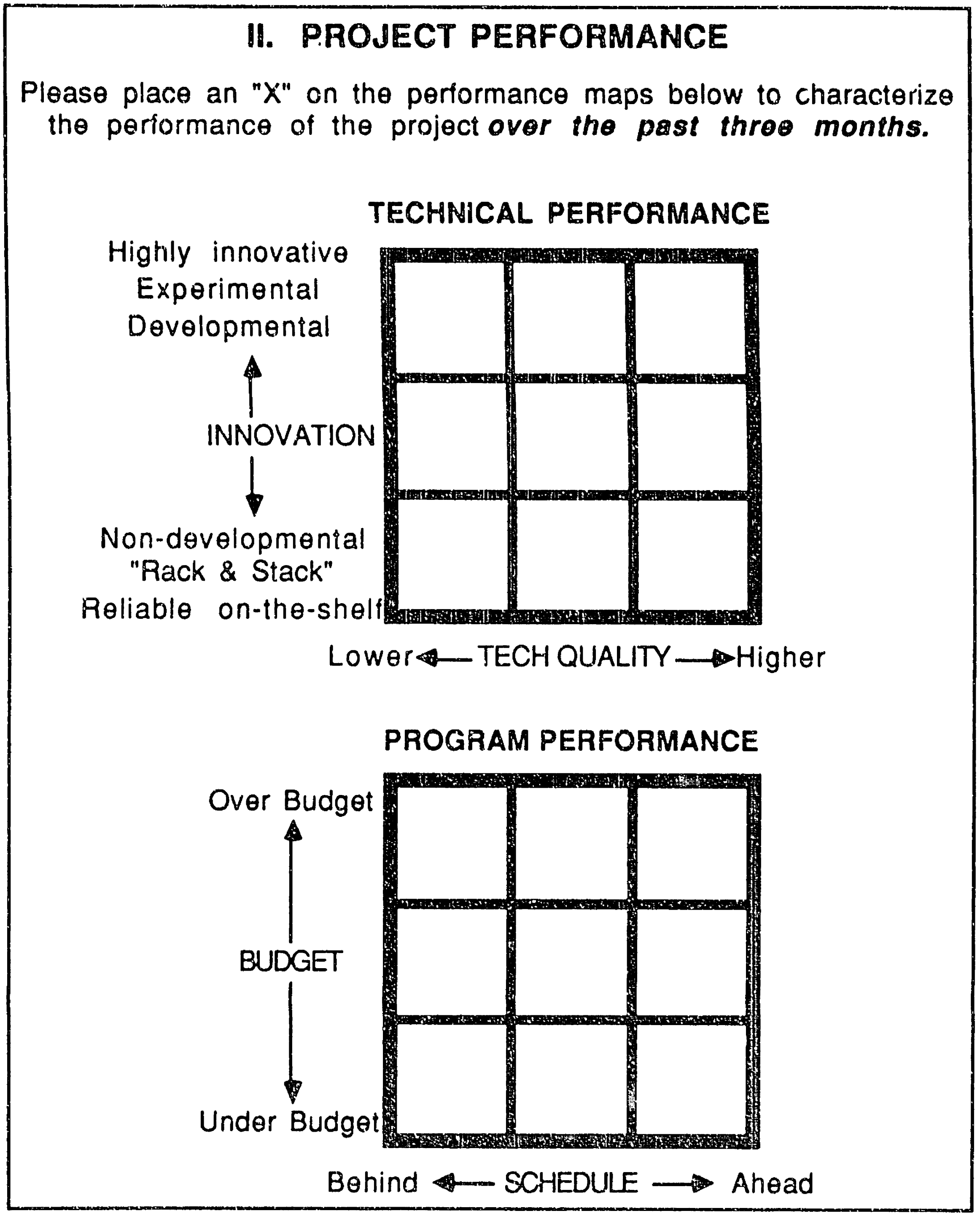
7. **WORK LOAD** Please characterize the average work load of engineers working on your project during the past three months:

   a. **Heavy**, leaving little time to keep up with professional reading, etc.

   b. **Moderate**, leaving some time for professional reading, etc.

   c. **Light**, leaving considerable time for professional reading, etc.

Figure 18a. Project Management Questionnaire, Front Side. Managers of engineering projects with engineers participating in the study received this questionnaire.



II. PROJECT PERFORMANCE

Please place an "X" on the performance maps below to characterize the performance of the project ***over the past three months.***

Figure 18b. Project Management Questionnaire, Back Side. The data from these responses were aggregated by project number with responses from engineers on the "daily" work surveys.

Responses, by company and project number, are summarized in Table 7.

Table 7. Summary of Project Characteristics at Companies 1 & 2							
Company	Project #	Tool Avail	Size	Tech Soph	Phase	Staffing	Workload
1	1	Limited	1	3	2	Fully	Moderate
1	2	Limited	5	1	5	Fully	Moderate
1	3	Advanced	1	1	4	Fully	Heavy
1	4	Basic	4	3	4	Fully	Heavy
1	5	Limited	5	3	4	Fully	Heavy
1	6	Limited	4	3	4	Fully	Heavy
1	7	Advanced	4	2	4	Under	Heavy
1	8	Basic	1	2	4	Under	Heavy
1	9	Advanced	1	2	4	Under	Heavy
1	10	Limited	1	1	6	Fully	Heavy
1	11	Advanced	1	3	3	Fully	Moderate
1	12	Limited	2	1	4	Fully	Moderate
1	13	Advanced	1	1	4	Fully	Moderate
1	14	Limited	1	1	5	Fully	Heavy
1	15	Basic	1	3	5	Fully	Moderate
1	16	Limited	2	2	4	Fully	Heavy
1	17	Limited	2	2	6	Fully	Moderate
1	18	Limited	2	2	2	Fully	Heavy
1	19	Limited	4	3	2	Fully	Heavy
1	20	Advanced	1	3	1	Under	Moderate
1	21	Limited	1	3	1	Under	Heavy
2	1	Advanced	1	1	6	Fully	Moderate
2	2	Limited	1	3	6	Under	Heavy
2	3	Limited	1	3	4	Under	Heavy
2	4	Limited	1	3	4	Under	Heavy
2	5	Advanced	1	2	3	Fully	Moderate
2	6	Advanced	2	3	4	N/A	Heavy
2	7	Limited	1	3	3	Under	Heavy
2	8	Advanced	3	3	4	Under	Heavy
2	9	Limited	1	1	4	Under	Heavy
2	10	Advanced	1	3	5	Fully	Heavy
2	11	Advanced	1	2	4	Fully	Heavy

Project size: 1=2-5, 2=6-10, 3=11-20, 4=21-50, 5=51+.
Tech soph: 1=Existing tech, in house; 2=Existing tech,not in house; 3=New tech must be developed.
Project phase: 1=IR&D, 2=Proposal, 3=Prelim Design/Develop, 4=Full Scale Develop, 5=Production, 6=Maintenance & Product Improvement.

Intercorrelations of Project Characteristics. A substantial inverse correlation ($r = -0.47$, significant at the 1% level) exists between the technical sophistication required, and the current phase of the project (Table 8). In general, the earlier a project is in its life cycle, the more likely it is that new technologies will have to be developed for the project to be successful.

Table 8. Correlation Matrix: Project Characteristics

	Avail	Size	Tech	Phase	Staffing	Workld	Comp
Computer Tool Availability in Work Area	1.00						
Project Size	-0.20	1.00					
Technical Sophistication Required	-0.08	0.12	1.00				
Current Phase of Project	0.09	-0.06	**-0.47**	1.00			
Project Staffing Level	0.21	0.09	0.06	0.08	1.00		
Workload of Engineers in Project	-0.17	0.13	0.20	0.07	-0.01	1.00	
Company	0.25	-0.32	0.18	0.10	0.11	0.20	1.00

Correlation coefficients **r** for project characteristics. Bold coefficients significant at the 5% (two-tailed) level ($r_{.10} = \pm 0.30$, $r_{.05} = \pm 0.35$, $r_{.01} = \pm 0.45$; sample n=32).

MEASURES OF PROJECT PERFORMANCE.

In interviews with managers at both companies, four project characteristics consistently emerged as measures of project performance. Two of these measures are associated with **productivity**, and are of primary interest to project managers:

a. Project schedule.

b. Project budget.

The other two are associated with **technical excellence**, and are of primary interest to technical managers:

c. Quality of project technical work.

d. Innovativeness of project technical work.

Using these four measures, project performance evaluations for the thirty-two projects are summarized in Table 9, and discussed in greater detail later in this Chapter.

Table 9. Project Performance Summary					
Company	Project #	Technical		Program	
		Innovation	Quality	Budget	Schedule
1	1	Moderate	Moderate	On	On
1	2	Low	Moderate	Under	Behind
1	3	Low	Moderate	On	On
1	4	Moderate	Moderate	On	On
1	5	Moderate	Moderate	Over	Behind
1	6	Moderate	Moderate	Over	Behind
1	7	Low	Moderate	Over	Behind
1	8	Low	Moderate	Under	Behind
1	9	Low	Moderate	Under	Behind
1	10	Low	Moderate	Under	On
1	11	Moderate	Moderate	On	On
1	12	Low	Moderate	On	On
1	13	Low	Moderate	On	Behind
1	14	Moderate	Moderate	On	On
1	15	Low	High	Over	Behind
1	16	Low	Moderate	On	On
1	17	Moderate	Moderate	On	On
1	18	Moderate	Moderate	On	On
1	19	Low	Moderate	On	On
1	20	High	Moderate	Under	Behind
1	21	Moderate	Moderate	On	Behind
2	1	Low	Moderate	On	On
2	2	Moderate	Moderate	On	Behind
2	3	Moderate	Moderate	Under	Behind
2	4	Moderate	High	Over	Behind
2	5	Moderate	High	Under	Behind
2	6	High	High	On	Behind
2	7	High	Moderate	On	Behind
2	8	High	Moderate	Over	Behind
2	9	High	High	Over	Ahead
2	10	Moderate	High	Over	Behind
2	11	High	Moderate	On	On

Measures of Productivity - Schedule and Budget.

Project schedule is a measure of a project's actual progress against a planned timeline (percent completion versus time), while project budget is a measure of its actual expenditure against a planned budget (percent budget versus time). A project's progress and expenditures are reported regularly by project leaders to their management, and are the most commonly used tracking measures of project performance.

On the project performance questionnaire, managers were asked to rate the schedule and budget performance of their project on a three level ordinal scale (ahead, on, behind schedule; over, on, under budget). Schedule and budget performance data were collected from twenty-one engineering project teams from Company 1, and eleven teams from Company 2 (Table 9; summary Table 10). In general, project leaders at Company 1 are more successful in keeping their projects on schedule and on/under budget than their counterparts at Company 2.

Table 10. Project Schedule and Budget Summary Statistics

Company:	1		2	
Sample size:	n=21		n=11	
Schedule		%		%
Behind	10	48%	8	73%
On Schedule	11	52%	2	18%
Ahead	0	0%	1	9%
Budget				
Under	5	24%	2	18%
On Budget	12	57%	5	36%
Over	4	19%	4	45%

Correlations between project performance measures and other project characteristics are summarized in Table 11. Note the substantial negative correlations between schedule, required technical sophistication ($r = -0.33$) and higher quality ($r = -0.40$). That is, high-tech projects and "high quality" projects are substantially more likely to be behind schedule. Similarly, note the substantial intercorrelation between the two performance measures, quality of work and project budget (r = 0.33). Not only are "high quality" projects more likely to be behind schedule; they are also more likely to be over budget as well.

Table 11. Correlation Matrix: Project Performance					
Correlation with Project Characteristics					
	Tech Soph	Phase	Size	Staffing	Workload
Project **Budget** Performance	0.26	0.09	0.25	0.00	0.23
Project **Schedule** Performance	-0.33	0.17	-0.05	0.08	-0.13
Correlation with Other Project Performance Measures					
	Innovative	Quality	Budget	Schedule	Company
Project **Budget** Performance	0.20	0.33	---	-0.13	0.16
Project **Schedule** Performance	0.22	**-0.40**	-0.13	---	-0.33
Correlation coefficients r for project performance. Bold coefficients significant at the 5% (two-tailed) level ($r_{.10} = \pm 0.30$, $r_{.05} = \pm 0.35$, $r_{.01} = \pm 0.45$; sample n=32).					

(Note: An overall project performance measure consisting of combined budget and schedule performance was also evaluated, to determine if project leaders were "robbing Peter to pay Paul" by playing schedule against budget. No significant findings resulted from this exercise.)

Schedule.

Most of the sampled Company 1 projects (52%) are on schedule, while the remainder are behind (Table 10 and Figure 19); none projects are rated as being ahead of schedule. By contrast, the majority (73%) at Company 2 projects are behind schedule, while only two (18%) are on schedule, and one (9%) is ahead of schedule.

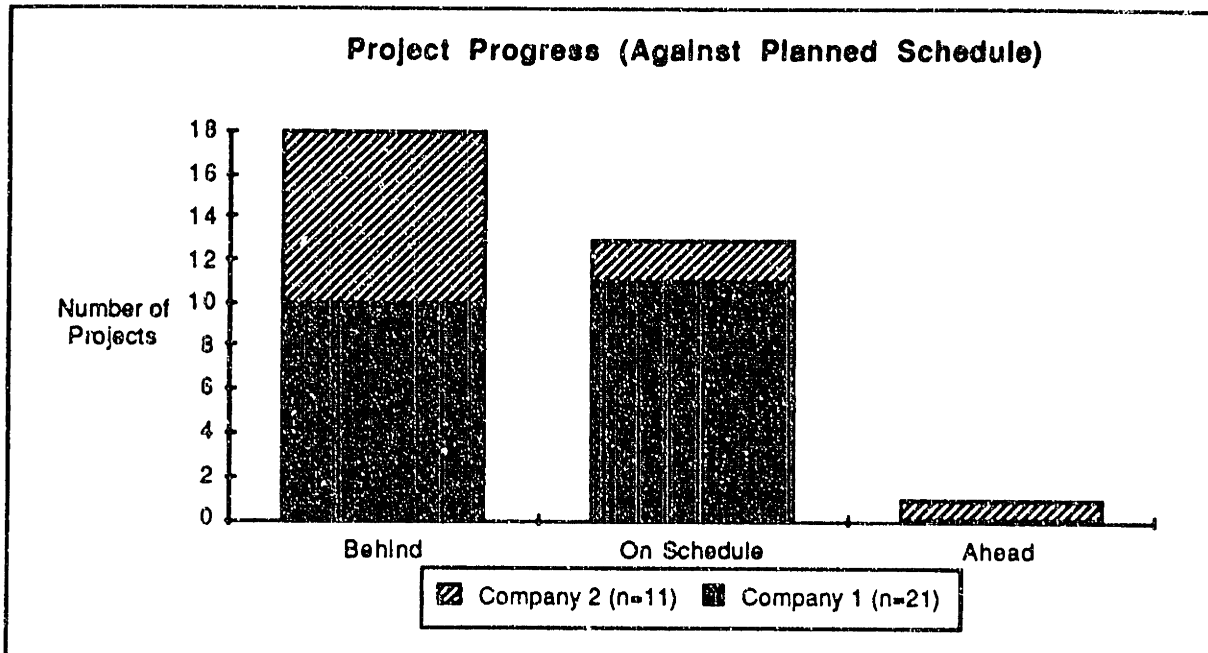


Figure 19. Distribution of project schedule data for Companies 1 & 2 (1988).

"High-tech" projects requiring the development of new technologies are somewhat more likely (r=–0.33) to be behind schedule (Table 11). "High-quality" projects are also substantially more likely (r= -0.40) to be behind schedule. When correlating computer use with schedule, we need to control for both required technological sophistication and the quality of work.

Budget.

The samples of project budget are more normally distributed than the samples of schedule (Figure 20). However, while only one-fifth (19%) of Company 1 projects are over budget, almost half (45%) of Company 2 projects have "busted the budget" (Table 10).

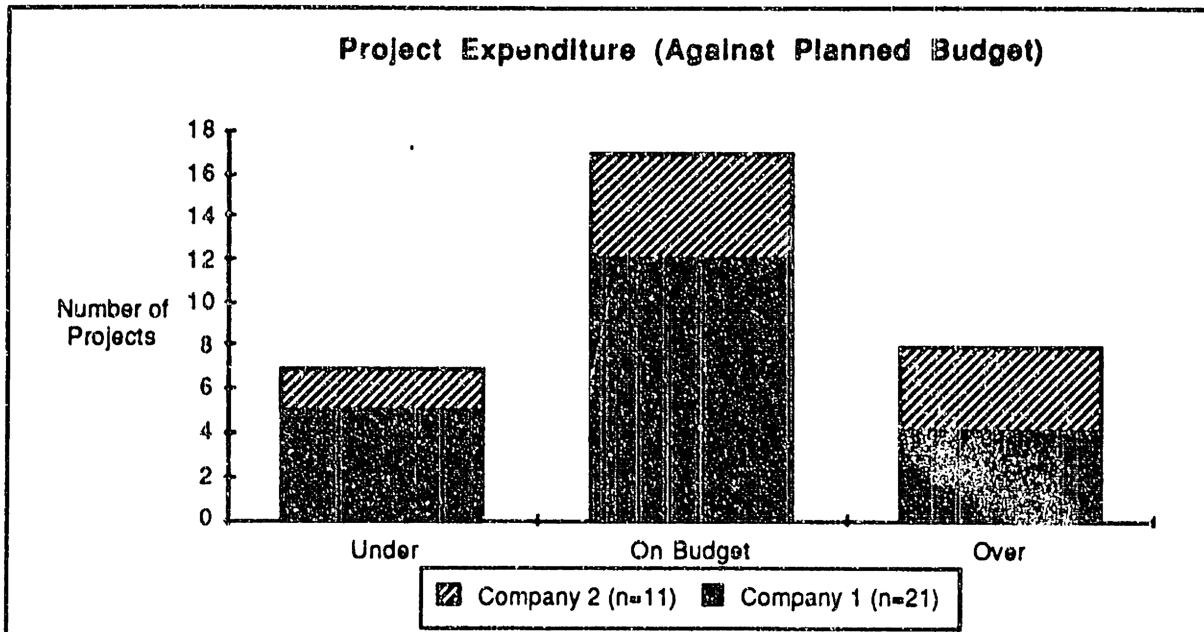


Figure 20. Distribution of project budget data for Companies 1 & 2. (1988).

"High-tech" projects requiring the development of new technologies are slightly more likely (r=0.26) to be over budget; this is because high-tech projects are more likely to "slip", requiring more effort (and time) to achieve desired results, than more mundane "rack-and-stack" projects. (Note: A "rack-and-stack" project is one which predominantly uses existing components, which are purchased (not designed!) by the engineer, placed in racks, and stacked inside the enclosure... a "bread and butter" form of engineering work, though not terribly innovative). Larger projects are also slightly more likely (r=0.25) to slip their budgets.

Measures of Technical Excellence - Quality and Innovativeness.

Quality and innovativeness of a project's technical work are more qualitative assessments of project performance. Project leaders generally desire their products to be of high quality and (in some cases) innovative design, both to satisfy product performance requirements and enhance the reputation of their product line. Engineering managers desire innovative and high quality engineering work to enhance the technical reputation of the firm, and minimize costly redesigns or production inefficiencies traceable to poor design.

Whereas Company 1's forte is in keeping projects on schedule and budget (Table 10), Company 2's strong suit is in innovative and high quality work (Table 12).

Table 12. Technical Performance Summary Statistics				
Company:	1		2	
Sample size:	n=21		n=11	
Quality		%		%
Low	0	0%	0	0%
Moderate	20	95%	6	55%
High	1	5%	5	45%
Innovation		%		%
Low	11	52%	1	9%
Moderate	9	43%	5	45%
High	1	5%	5	45%

Correlations between technical performance measures (e.g. quality, innovativeness of work) and other project characteristics are summarized in Table 13, and addressed in greater detail later in this chapter. Note the substantial positive correlations between innovativeness of project work and required technical sophistication ($r = 0.44$), and early project phase ($r = -0.35$; Table 13).

Table 13. Correlation Matrix: Technical Performance with Project Performance Characteristics					
Correlation with Project Characteristics					
	Tech Soph	Phase	Team Size	Manning	Workload
Innovativeness of Project Work	**0.44**	**-0.35**	-0.13	0.17	0.20
Technical **Quality** of Project Work	0.14	0.03	-0.25	0.34	-0.02
Correlation with Other Project Performance Measures					
	Innovative	Quality	Budget	Schedule	Company
Innovativeness of Project Work	- - -	0.23	0.20	-0.22	**0.55**
Technical **Quality** of Project Work	0.23	- - -	0.33	**-0.40**	**0.50**
Correlation coefficients r for project technical performance. Bold coefficients are significant at the 5% level ($r_{.10} = \pm 0.30$, $r_{.05} = \pm 0.35$, $r_{.01} = \pm 0.45$; sample n=32). Innovative, high quality work is more likely to be found at Company 2.					

Quality.

While projects at Company 2 are evenly distributed between moderate and high quality work, all but one project was rated as having "moderate" quality at Company 1 (Figure 21; Table 12). This phenomenon is related to the market differences between the two companies. The dominant form of contract work at Company 1 is the **fixed-price** government contract. There is no incentive for providing any "excess" quality over and above that required in the product specification; in fact, since higher-than-required quality may cost more engineering effort, budget, schedule and profitability may be adversely affected, possibly resulting in contract penalties. The "secret" to profitability under fixed price contracts is to get "just enough" quality to "meet spec"... but keep it on schedule and under budget! By contrast, high quality products are felt to be a "win discriminator" in the competitive commercial market in which Company 2 must survive and prosper.

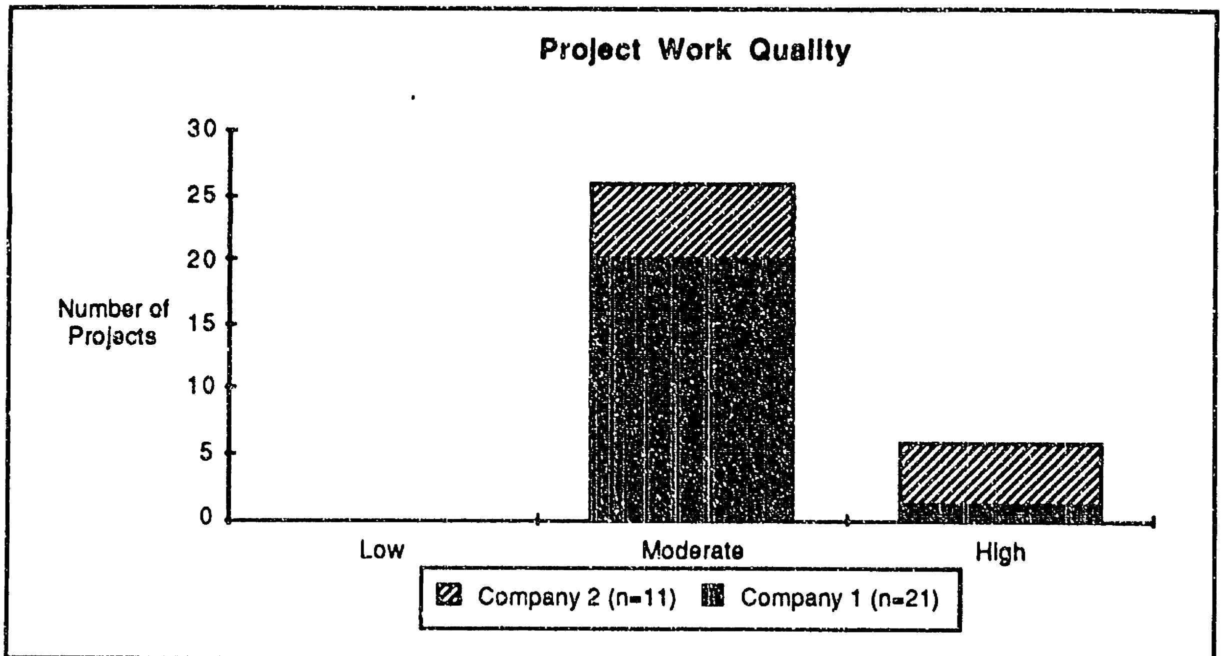


Figure 21. Work quality distributions at the two companies. (1988).

Significant correlations exist between quality, budget (r = 0.33) and schedule (r = -0.40), significant at the p=.10 level or better (Table 13). That is, projects rated as producing high quality work are somewhat more likely to be over budget, substantially more likely to be behind schedule, or both. It could be that quality improves as the engineers gain more time to perfect their designs. Since engineering time costs money (about $75 an hour in 1988), higher quality is bought at the cost of increased labor, making the project more costly. It is also possible that a "higher quality" assessment could be justification for managers with projects which are over budget and/or behind schedule.

Innovativeness.

The sample data from Company 1 (Figure 22) are skewed toward less innovation, not unusual for defense contractors **required to minimize technical risk**. By contrast, the sample data from Company 2 are skewed toward more innovation, necessary for Company 2 product lines to compete in a fast-paced marketplace characterized by short product life cycles. Company 2, using computer aided engineering, can go from initial product concept through design, development, "alpha" internal test, "beta" customer test, production and delivery in under two years.

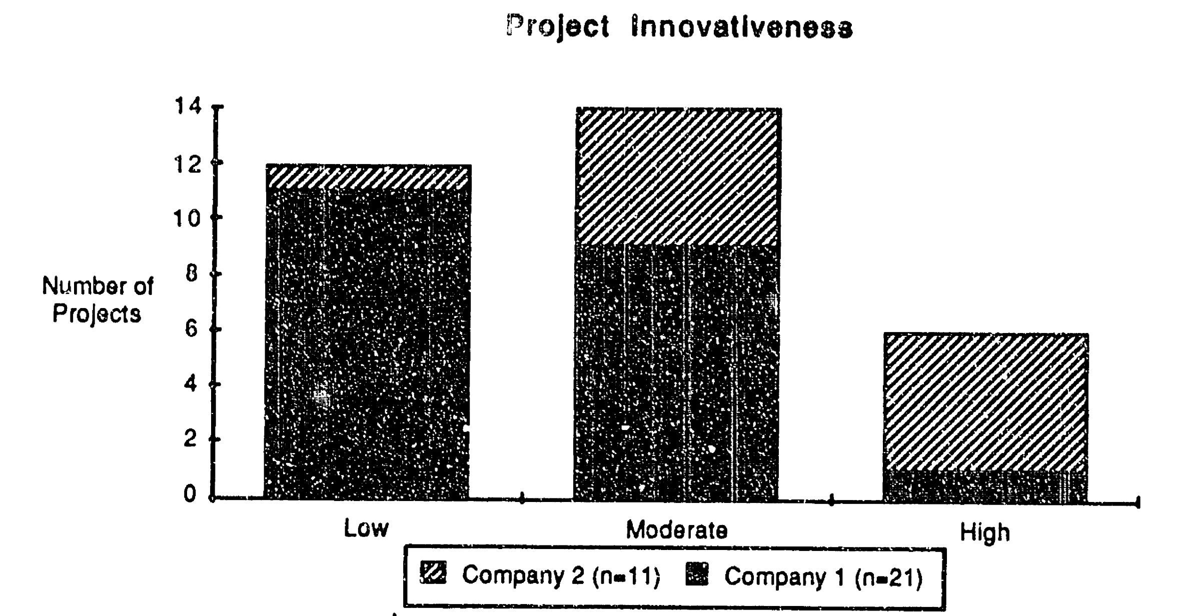


Figure 22. Innovativeness of project work at the two companies. (1988).

Projects requiring the development of new technologies (tech; r=0.44) and projects earlier in their life cycle (phase; r=–0.35) are substantially more likely to be rated as being innovative (Table 13). (Recall that phase and tech are also substantially correlated at r=–0.47; Table 8.) Projects at Company 2 are also more likely to be rated as innovative (r=0.55). When correlating computer use with innovativeness, we need to control for phase, technology, and company effects.

CHAPTER 5. COMPUTER TOOLS AND ENGINEERING PROJECT PERFORMANCE.

A substantial body of literature suggests that computer tools can improve the technical performance of engineers in a number of different ways, including:

1. *Making engineers more productive.* This, in turn, leads to lower engineering labor cost, shorter design cycles, and accelerated product delivery. In a highly competitive marketplace with high innovation rates and short product life cycles, this can be a significant advantage.

2. *Improving the quality and innovativeness of engineering work.* Computer tools enable the engineer to perform calculations with a speed and precision several orders of magnitude better than previously possible, allowing more design iterations and more alternatives to be considered. The 3-D graphics interface provided by many CAD tools enhances the engineer's visualization and problem solving ability. Most importantly, computers can enable engineers to design complex systems *well beyond the scope* of those possible using manual methods.

3. *improving technical communication.* By improving the efficiency of communication between upstream and downstream members of a project team, group performance can be improved. The design of group automation systems requires careful attention

to organizational interface design (user interface design on a group scale).

4. *Improving the quality of working life.* Computer tools can enrich engineering jobs, leading to greater challenge, more creative tension, higher job satisfaction and improved performance.

LITERATURE REVIEW.

Making Engineers More Productive

A report for the National Science Foundation asserts that CAD can significantly reduce the time and cost of product design, and contribute to industrial competitiveness, especially if CAD is used by basic industries (General Electric/Corporate Research & Development et. al., 1976). Increased use of robotics and CAM have been suggested as a strategy for improving a firm's competitive posture on the international marketplace (Gold, 1982). Automation technology has been shown to be a positive factor in the production function (Nelson & Winter, 1977).

An important factor in improving engineering productivity and the firm's competitive posture is the shortened development times permitted by computer tools (GE/CRD et al, 1976; Gold, 1982; Johnson, 1984). IBM reduced their development time of the Model 3081 mainframe computer by over 2/3 using CAE (Swerling, 1982). Silicon compilers can design complex electronic chips with millions of gates in just a few hours, a job which used to take several months with less sophisticated tools (Wallich,1983b), and which was literally impossible without the tools (Miley, 1980). Automated circuit board testing permits the exhaustive checking of electronic circuits previously considered "untestable" due to their complexity (Tullos, 1983). Even basic office automation tools like word processors can shorten the technical documentation cycle by 50 percent (McDermott, 1984; Miller & Kelley, 1984).

Case studies of CAD and CAE implementation suggest a learning curve with initial, short-term drops in productivity, followed by gains (Figure 23). In one case study of PC-based CAE at a picture-tube division, using the number of engineering drawings per engineering man-hour as a productivity measure, an initial dip of 25 percent productivity loss during first three months was followed by a 2:1 improvement after 6 months, and a 3:1 improvement after 12 months (Miller & Kelley, 1984). In another study involving six companies and four strategies for implementing CAD, data on perceived project productivity improvements suggested productivity gains which asymptotically approached 25 percent after 3 or more design projects, following initial negative productivity losses of 0 percent - 25 percent depending on automation strategy (Gagnon and Mantel,1987). Other case studies showed long-term productivity gains ranging from 1.25:1 for highly complex drawings to 4.5:1 for simple logic drawings, with higher productivity realized for simpler, more repetitive tasks (Machover & Blauth, 1979). (See Appendix C, "Compiled List of Productivity Multiplication Factors Attributed to CAD/CAM".)

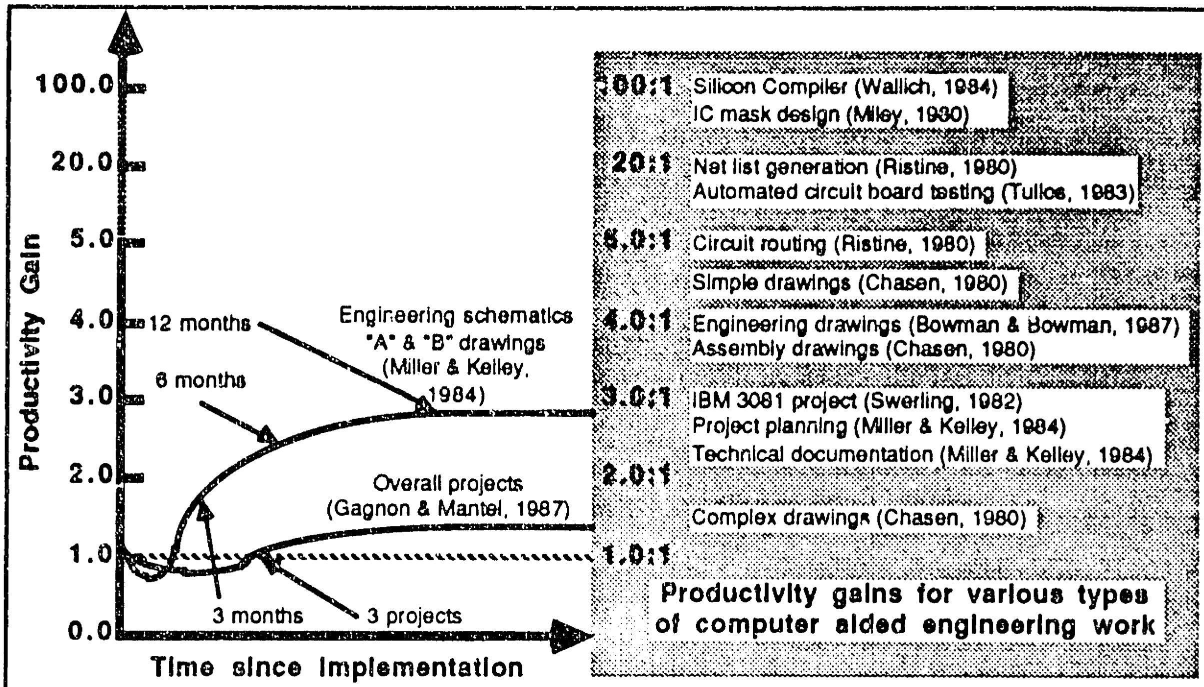


Figure 23. Productivity gains reported in different CAE implementation studies. The left-hand portion of the figure shows how productivity gains change with time. Note the initial "learning curve" dip in productivity, followed by productivity gains. In general, productivity gains increase with increasing task complexity and repetitiveness.

Using computer tools to leverage manpower, project teams may achieve the planned results in less time than planned, or with reduced labor cost, under the planned budget.

Because of the cost savings realized by CAD/CAM and CAE systems, return on investment (ROI) can occur quickly (under six months) for less ambitious automation systems using PC's and entry level workstations (Miller & Kelley, 1984). More extensive and costly systems (with a greater potential for productivity improvements) can show a return on investment in eighteen months or less (Chasen, 1980).

Improving Quality and Innovation in Engineering Work.

The quality and innovativeness of engineering work (collectively referred to as "technical excellence" by one engineering company studied) directly affect the quality, performance, and cost of the product and/or process under development.

Computer tools can be used to enhance the quality of engineering work in several fashions. One way is to use the speed and accuracy of computers to enable engineers to design more sophisticated systems, evaluate more alternatives, and (having selected a design approach) make more design iterations and refinements. While enjoying the 3:1 productivity gains of CAD, IBM simultaneously optimized the Model 3081 mainframe's performance through increased simulation (Swerling,1982).

Another way is to use improved tools that better support the human problem solving process. An important contribution of modern CAD/CAM and CASE tools to technical problem-solving is improved spatial visualization using 2-dimensional and 3-dimensional graphics (Chasen & Dow, 1979). Hypertext systems, which support free association and browsing, are being adopted by increasing numbers of RD&E firms like McDonnell-Douglas for complex system analysis and design (Fiderio, 1988).

Computer tools can also aid engineers in developing innovative solutions to problems. Exploiting the computer's speed, engineers can examine and evaluate more alternative approaches to their design, improving the chances for finding a serendipitous solution to the problem. Parallel examinations of different approaches offer improved insight into the problem (Marples, 1961).

A study of 1300 engineers at eleven RD&E labs also suggests that diversity (a creative tension between sources of stability and challenge at the workplace) stimulates idea generation (Pelz, 1967). For engineers, overall productivity peaks when only half to three-quarters of their time is spent in "strictly technical" activities. Participation in teaching, administration, and other activities is correlated with improved performance (Pelz and Andrews, 1967). By exploiting some of the slack time resulting from increased productivity, engineers can participate in more diverse work (Trist, 1981), enriching their jobs and stimulating this creative tension.

Technical Communication.

Technical communications, both inside and outside the firm, were shown to be a factor in one-third of five hundred successful innovations studied by Marples (1969). Engineers rely heavily on customers, vendors, and fellow engineers for information needed to do their work (Allen, 1966b). Effective technical communication, whether formal (written specifications and blueprints, technical papers) or informal (hallway conversations, back-of-napkin sketches), is vital to the success of engineering projects (Allen, 1977).

Effective communication, both internal and external to project teams, is correlated with technical performance and innovativeness (Allen, 1977). Innovative firms show a strong reliance on outside sources of information for idea generation (Myers & Marquis, 1969). Electronic mail, particularly information-focusing tools such as online clipping services and "information lens" systems can provide the engineer with access to these information sources (Malone, 1985).

Designing Tools for Groups.

The group-oriented nature of engineering work has significant implications for the design of computer systems for engineering organizations. Computer aided engineering can best be looked upon in terms of **group technology**, automating the entire work group environment (Wallich, 1983a; Bowman and Bowman, 1987). About one-fourth (23%) of an engineer's (and project team's) average day is spent in technical communication (Figure 7). Automating the group can reduce this communication overhead by two-thirds or more (Schlefer, 1983; Miller & Kelley, 1984).

Just as a user interface connects a human user to the capabilities provided by a computer, an organizational interface connects human users to each other and to the capabilities provided by computers. Most of the computer tools in use today are designed to facilitate separate problem solving by isolated individuals. For group-oriented activities, such as engineering projects, it is important to design a synergistic organizational interface that facilitates problem solving by groups of people (Malone, 1985).

Widespread use of computers within organizations can substantially decrease unit costs of coordination, with respect to both the transmission and processing of information (Malone & Smith, 1984). Product-oriented firms can shift towards functionally organized ones, taking advantage of the reduced coordinating cost and increased flexibility of the new systems. Organizations can employ desirable organizational structures that would otherwise be impractical due to the effects of high subsystem interdependence, short project durations, or rapid technological change (Allen, 1985).

The Dilemma - Balancing Productivity and Innovativeness.

There is a "dark side" to computer tools. Productivity and innovativeness, competing for the same resources, can be at odds. In a historical study of innovation and productivity in the automobile industry, simultaneous nurturing of both productivity and innovativeness was described as a dilemma:

> Stated generally, to achieve gains in productivity, there must be attendant losses in innovative capability; or conversely, the conditions needed for rapid innovative change are much different from those that support high levels of production efficiency. ...Is a policy that envisions a high rate of product innovation consistent with one that seeks to reduce costs substantially through extensive backward integration? Would a firm's action to restructure its work environment for employees so that tasks would be more challenging, require greater skill, be less repetitive, and embody greater content be compatible with a policy that proposed to eliminate undesirable direct labor tasks through extensive process automation? "No" is the answer prompted by the model to each of these questions [which] suggests a pair of actions that are mutually inconsistent. (Abernathy,1978)

This may be especially true with computer tools, where major efficiencies are gained by "cloning" and tailoring solutions to previous (and different) problems. Uniformity and homogeneity of designs can result, stifling creativity and product performance through the acceptance and implementation of sub-optimal designs that happen to be on the solution menu (Naisbitt, 1983). Nor do artificial intelligence (AI) and expert systems technology promise otherwise. Researchers are having difficulty bestowing such systems with the creative spark of human ingenuity (Dreyfus & Dreyfus, 1986). Thus, although productivity may improve by replacing skilled human problem-solvers with more efficient (though less imaginative) machine counterparts (operated by less skilled operators), design quality may suffer (Wallich, 1984b).

HYPOTHESES.

So, who is right? The optimists, the pessimists, or both? Taking the optimistic side, we pose two more hypotheses relating use of computer tools by engineers with higher performance.

Hypothesis 2: Projects for which engineers ma greater use of computer tools, as measured by the percentage of time computers are used by engineers to do their work, are more likely to be:

a. On or ahead of **schedule**, as measured by progress of projects against their planned schedule.

b. On or under **budget**, as measured by status of project budgets against their planned budgets.

Hypothesis 3: Projects for which engineers make greater use of computer tools, as measured by the percentage of time computers are used by engineers to do their work, are more likely to have more innovative work, as evaluated by project managers.

CORRELATIONS BETWEEN COMPUTER USE AND PROJECT PERFORMANCE.

Computer Use and Project Performance - Schedule and Budget.

In the following section, we will compute **partial correlation** coefficients between **schedule and budget with computer use** to support engineering work (overall, and related to specific kinds of work such as analysis, design, and development). Project performance is the dependent variable; computer use is the independent variable. Controlling for the sophistication of available tools suppresses a strong company difference in the percentage of time computers are used by engineers (the independent variable; Table 5). We also control for the level of technical sophistication required by the project and work quality, both previously shown to be substantially correlated with project schedule and budget, the dependent variables.

Although the percentage of time engineers use computers is uncorrelated with project schedule, projects which make greater use of computer tools are slightly more likely to be under budget ($r = -0.33$, significant at the $p = .10$ level; Table 14). This supports acceptance of Hypothesis 2-b, that **use of computer tools is correlated with higher project performance** as measured by being on or under budget. (Note: Company is not controlled for in this correlation. When company is controlled for, the results remain the same. This is because the sophistication of available tools is the dominant influence on computer use.)

Table 14. Partial Correlation Coefficients: Budget and Schedule vs Percentage of Overall Computer Use (Project n = 32)		
Partial Correlation Control Variables:	Budget Performance	Schedule Performance
None	-0.24	-0.09
Sophistication of Available Tools	-0.26	-0.01
Required Technical Sophistication	-0.23	-0.09
Quality of Work	**-0.32**	+0.01
Soph of Avail Tools, Reqd Tech Soph, Quality	**-0.33**	+0.04
Correlation coefficients **r**. Bold coefficients are significant at the 10% (two-tailed) level ($r_{.10}$ = ±0.30, $r_{.05}$ = ±0.35, $r_{.01}$ = ±0.45; sample n=32).		

Computers and Project Performance - Quality and Innovation.

Table 15 shows the **partial correlation** coefficients between **quality and innovativeness with computer use** to support overall engineering work. As in Table 14, project performance is again the dependent variable; computer use is the independent variable. We control for the sophistication of available tools to suppress a strong company effect on the independent variable, computer use. We also control for other extraneous variables such as the level of required technical sophistication, project phase and project schedule, previously shown to be substantially correlated with technical performance.

Table 15. Partial Correlation Coefficients: Quality and Innovativeness vs Percentage of Overall Computer Use (Project n = 32)		
Partial Correlation Control Variables:	Quality of Work	Innovativeness
None	+0.18	-0.06
Sophistication of Available Tools	+0.14	-0.14
Required Tech Sophistication	N/A	-0.04
Project Phase	N/A	-0.03
Project Staffing	+0.17	N/A
Project Schedule	+0.13	N/A
All Applicable	+0.12	-0.14
Correlation coefficients r for project technical performance. ($r_{.10}$ = ±0.30, $r_{.05}$ = ±0.35, $r_{.01}$ = ±0.45; sample n=32).		

At first glance, the use of computers would seem to have little correlation with technical performance, other than for slight correlations with higher quality and lower innovativeness. However, when the correlation coefficients are computed between innovativeness of project work and percentage of computer use by work category, an interesting pattern emerges (Table 16). At the beginning of the engineering cycle (analysis), increased use of computers, controlling for the sophistication of available tools and extraneous factors such as project phase, is negatively correlated with innovativeness ($r = -0.30$) and overall technical performance ($r = -0.32$), significant at the $p=.10$ level. However, at the other end of the engineering cycle (development), use of computers by engineers is substantially correlated with more innovativeness ($r = 0.35$), significant at the $p=.05$ level. And, while use of computer tools in the documentation and communication area is positively correlated with higher quality ($r = 0.22$), it is (not surprisingly) correlated with less innovative work ($r = -0.21$).

Table 16. Partial Correlation Coefficients: Technical Performance vs Computer Use by Work Category (Project n = 32)

Performance Variable:	Quality of Work	Innovativeness
Control Variables:	Soph of Avail Tools, Project Staffing, Project Schedule	Soph of Avail Tools, Reqd Tech Soph, Project Phase
Computer Use (Analysis)	-0.13	**-0.30**
Computer Use (Design)	-0.01	-0.01
Computer Use (Development)	+0.01	**+0.35**
Computer Use (Documentation & Communication)	+0.22	-0.21

Partial correlation coefficients **r** for project technical performance. Bold coefficients are significant at the 10% (two-tailed) level ($r_{.10}$ = ±0.30, $r_{.05}$ = ±0.35, $r_{.01}$ = ±0.45; sample n=32).

Innovativeness and Computer Tools. Why the dramatic difference in the correlation coefficients as one moves along the engineering cycle from initial anlaysis, through design, to engineering development? I believe there are two mechanisms at work. The first is related to the degree of structure inherent in the work, and the "breadth" (or bandwidth) of the work (Figure 24). The second is related to the "cloning" of solutions using computer tools.

Computer Tools and the Structure of Work. Most computer tools used by engineers today have sharply focused functionality; each tool is designed to do one kind of work (word processors are optimized for writing; drawing programs are optimized for drawing; spreadsheets are optimized for calculations, etc.). In fact, computer tools which support complex and highly specialized tasks (e.g. circuit design using CAD, requirements development and tracing using CASE) usually support only one structured method, technique, or algorithm. When used in their intended role, computer tools can leverage an engineer's productivity. When a computer tool is used to perform work outside its intended function, it may hamper the engineer's efficiency. Also, while creative adaptation of a computer tool for a new application may itself be innovative, trying to "force" a tool to do work for which it is not intended may have adverse impacts on technical performance.

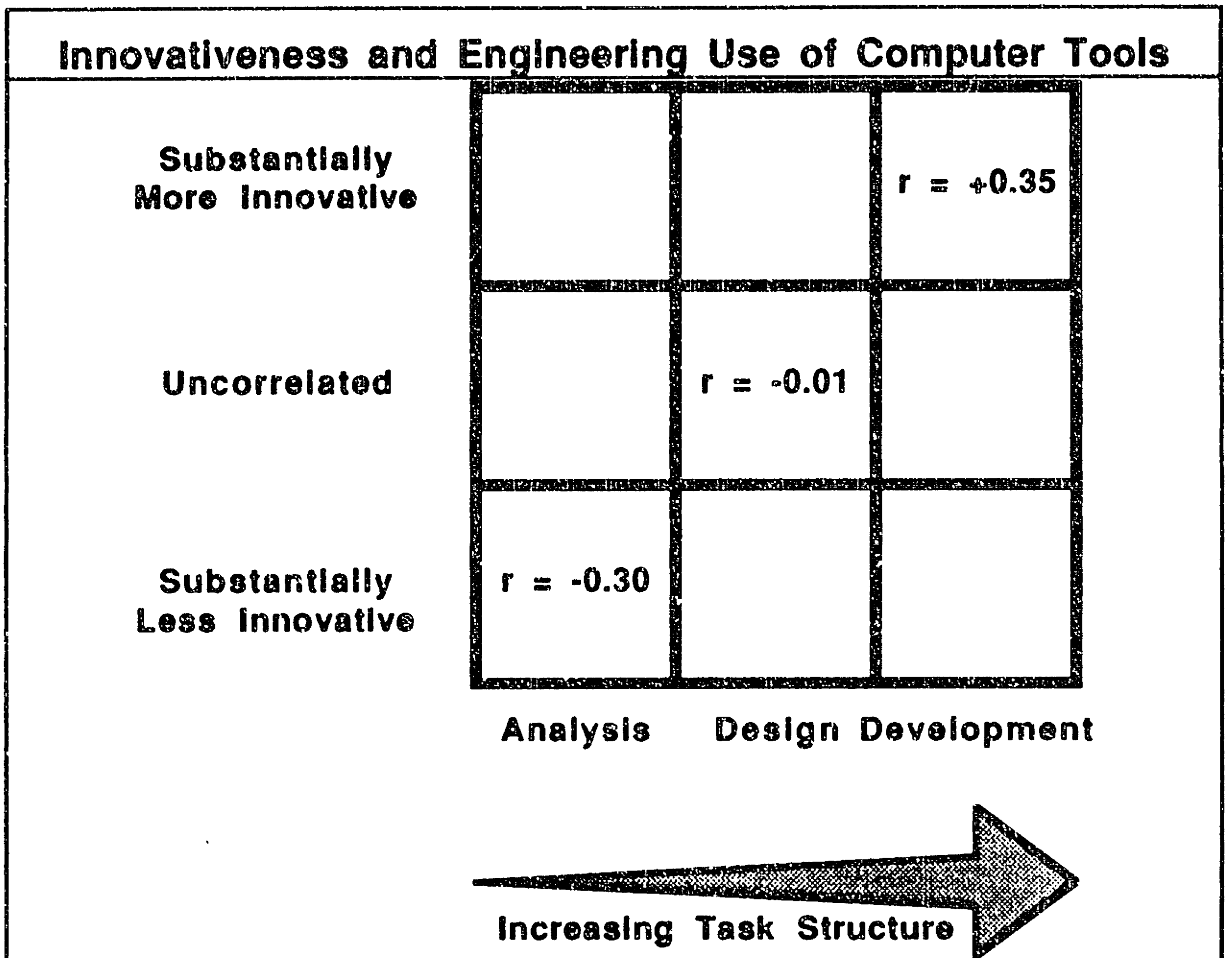


Figure 24. For highly structured tasks, like engineering development work, use of computers is substantially correlated with more innovative work. For loosely structured tasks, such as preliminary analysis and problem definition, use of computers is substantially correlated with less innovative work.

Generally, analysis work is not highly structured, precluding any one tool from supporting the analysis task. By contrast, engineering development is highly structured ("cook-book", "rack-and-stack", and "turn the crank" are terms of endearment used by engineers to describe this phase of engineering work). Thus, one would expect that supporting engineering development is the computer tool's forte; this is well borne out by the evidence (Table 16). CAD and

CAE tools are well suited to boost the efficiency of engineers, creating slack time which, in turn, can be managed to yield more time for creative work.

Computer Tools and Homogeneity. As suggested by Naisbitt (1983), the desire to "clone" previous solutions to problems is high when using computer tools, since the re-use of previous solutions is a key part of the computer's ability to leverage productivity. The time and effort needed to set up a new solution for each problem is at odds with higher productivity. However, the re-use of old solutions leads to homogeneity in problem-solving approaches which, almost by definition, stifles the development of innovative solutions to problems (Figure 25). Further, old solutions may represent a "negative biasing set", resulting in suboptimal solutions to the current problem. The substantial negative correlation between innovativeness and the use of computers for analysis work tends to corraborate Naisbitt's argument.

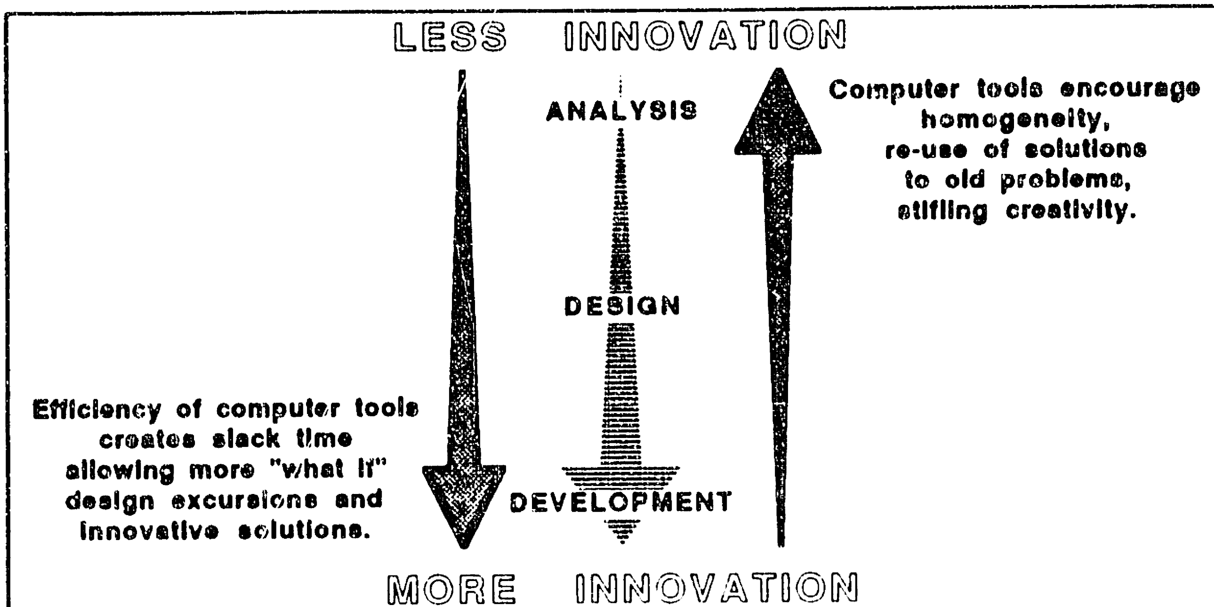


Figure 25. The efficiency gained by the use of computer tools creates slack time which, in turn, can be used to support innovative activity. On the other hand, the tendency to "crank out" homogenous solutions stifles creativity, balancing the efficiency benefits of computer tools. Both can currently be achieved only for structured tasks like engineering development, for which computer tools are well suited.

Thus, **Hypothesis 3 is only partially supported** by the data. More use of computer tools for engineering development is substantially correlated with more innovative work; by contrast, more use of computer tools in engineering analysis is substantially correlated with less innovative work!

SUMMARY AND LESSONS LEARNED.

Engineering work is a rich assortment of technical and non-technical tasks. Engineers spend just under half of their average day working on technology-related tasks traditionally associated with engineering work. Engineers also spend about forty percent of their time communicating in some form.

Engineers at the two research sites also spend about half of their day working with computer tools. At Company 1, engineers spend about forty percent of their average day working with computers, while engineers at Company 2, working in a "paperless office" environment, spend sixty percent of their day with computers. Roughly half of the computer use by engineers is in technology-related tasks such as analysis, design, and development. Roughly one-quarter of the computer use is in documentation and communication related tasks. Most engineers at both sites using the computer for word processing and editing. Another leading use of computers by engineers is in software development.

A number of intervening factors are strongly associated with the use of computer tools, while others are strongly associated with the performance of projects. Although significant differences exist between the use of computer tools at the two companies, controlling for the sophistication of tools available to engineers in their immediate work area dramatically eliminates statistically significant company-related differences in computer use patterns. Engineers and **project teams with access to more sophisticated tools are more likely to use computers** at both R&D firms. By controlling for the sophistication of available tools, it becomes possible to aggregate the computer use data for the two sites. Other extraneous and intervening factors, such as the level of technical sophistication required, project phase, and staffing levels, are correlated with computer use and performance at the two different R&D firms. These factors, and intercorrelations between measures of performance (work quality with project schedule and budget, for example), further complicate analysis of the relationship between use of computer tools and the performance of engineering projects.

Use of computer tools does improve the productivity of engineering project teams. After controlling for intervening and extraneous factors such as the availability of computer tools, level of technological sophistication required, and the quality of work, the **use of computer tools is correlated with projects being under budget** ($r = -0.33$, $N = 32$, $p < 0.10$).

While use of computer tools for preliminary analysis and problem solving is substantially correlated with less innovativeness ($r = -0.30$, $N = 32$, $p = 0.10$), the use of computer tools for engineering development work is substantially correlated with more innovativeness ($r = -0.35$, $N = 32$, $p = 0.05$). Thus, computer tool use is correlated with **less innovative work** when used to support engineering **analysis and problem solving** while they are correlated with **more innovative work** when used to support engineering **development**.

The reasons for this dichotomy are two-fold. Computer tools can make engineers much more efficient for certain types of tasks, allowing more time to be spent in innovative pursuits. However, much of this efficiency is achieved by cloning old solutions, which in turn encourages homogeneity, stifles innovation, and biases the engineer to use a convenient but suboptimal solution. In addition, computer tools tend to be highly focused, constraining the "bandwidth" of the problem solving process to fit the capabilities of the computer tool.

Recommended Strategy.

A simple, yet effective, strategy for managing the use of computer tools for engineering work emerges from the conclusions of this research:

1. **Create and manage slack.** Computer tools can be used to leverage individual and group productivity, creating slack in manpower resources. This slack should then be managed, resulting in some combination of more innovation-stimulating tasks for engineers, and increased productivity for the firm.

2. **Use appropriate tools.** Since engineering work includes many different types of tasks, engineers should be provided with a versatile and complete "toolkit" of computer hardware and software tools. With today's software technology, computer tools best support highly structured, repetitive tasks, or tasks with substantial amounts of data or numerical manipulation. Use of computer tools with a narrow functional focus to support less-structured work, or work with "high cognitive bandwidth", may result in reduced performance. (Note: As software technology and the "electronic hierarchy" becomes more sophisticated, computer tools will be capable of leveraging productivity for an ever-widening range of engineering work.)

FOR FURTHER RESEARCH.

This research program has just begun to unlock the secrets of productivity and innovativeness gains due to the use of engineering computer tools. A lot of "interesting" research remains to be done. Unanswered questions include:

A study of computer tools designed for innovative problem solving. What kind of computer tools best support creative work? How does one design computer tools to encompass broadly scoped or loosely structured work? Is it possible to design computer tools which can stimulate creative problem solving, while simultaneously improving productivity? What is a good metric for structure of work?

A comparison of computer use between hardware and software engineers. Research at both Company 1 and Company 2 show differences in the kinds of work performed by hardware and software engineers, as well as differences in background. How do their use of computers vary? Is there a difference in the project performance correlation with computer use? If so, what moderator variables might explain the difference? Does the software engineer's "intrinsic expertise" with computer tools have any effect on the population correlation for computer use versus project performance?

A study of computer use as a function of tool environments. What constitutes a "useful" set suite of tools for engineers? What are the features of such a useful suite? Identify and evaluate motivators and barriers to the use of computer tools in greater detail.

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APPENDIX A. Company 1.

A.1. Impressions of an Engineer at Company 1.

I've been working half-time as a systems engineer with Company 1 for six years now. Systems engineer means you do a little bit of everything, like a "Jack of all Trades." And I have done a "little bit of everything" with Company 1. Some internal R&D, developing new algorithms and techniques for analyzing radar data.. Some market analysis and new-product concept development. Some preliminary hardware and system design for computer systems and data communication systems. I enjoy this work. I can still remember the first time a system I designed became production hardware, and went out the door. The creation of a successful machine, like the creation of a poignant, original song, is an intensely satisfying personal experience.

It's a good thing I enjoy this work, because the commuting is downright *awful*. The boring drive takes 45 minutes on a *good* day. Today, the morning fog and drizzle has slowed the expressway traffic to a crawl, and 45 minutes has only gotten me *halfway* there. I'm going to be late. Work starts at 7:30 AM (isn't that when farmers milk cows?) and ends at 4:15 PM. I have a 45 minute long official lunch period. Any discrepencies of 0.1 hour or more are to be duly reported on the time card. That's six minutes, Charlie. Bother.

Getting in late has at least one advantage. I can get a good parking spot near the door as one of the night-shift factory workers leaves for home. There are an awful lot of "reserved" parking spots here. All for managers. Engineers don't ever get them (unless they're managers). I wish I had one today, it would save me several minutes. I pull my ID badge out of the shirt pocket, show it to the guard at the entrance, open my briefcase for inspection. ("What's in the case?" "Just floppies for the PC." "Okay.") I hurry up the stairs, and make my way down a labyrinth of fuzzy-looking Steelcase® partitions . Let's see. Second hallway. Third door on left. Right. Third alley on the left. Left. Left again, into the work bay I share with three others. I wonder if this is what a lab rat feels like?

Things have been modernized here within the last couple of years. The biggest change is undoubtedly with computers. Just two years ago, we had a small handful of minicomputers with terminals hooked to them, clustered in a "terminal room." You had to get to the terminal room early in the morning, and "camp out" during the lunch hour, in order to get a terminal; God forbid if you ever left the terminal to eat lunch - someone else would grab it, and you wouldn't be able to get back on until after hours. Nowadays, the norm seems to be two terminals and a PC per four engineers, with the equipment located in the work ways. In this bay, we have two phones, two terminals, and a PC with a printer and network interface. Macintoshes® (Macs) are especially popular here. Over half of the engineering PC's in house are Macs; most of the remainder are PC's or clones. The engineers here seem to prefer the Mac, while the business and project management guys seem to lean towards the PC. My PC is an older model, one of the first in the plant. It's gotten "long in the tooth", but is still an effective tool. With its math coprocessor, it'll run the pants off an AT for engineering calculations. And it's still the *only* PC in the plant with a math chip! Oh well, "Age before beauty".

Two of my bay mates are here before me.. ("Hi, Bill. Hi, Mary." "Hey, Dave." "Hi, Dave. Hey, guess what, I found the gold key!") I take off my jacket, straighten my tie, sit down, and turn on my PC. Mary tells me about her latest progress in the computer game she's playing at home. Our talk moves from adventure games, to the latest stunt our customer pulled, to the architecuture of a new imaging processor we're building. By 9:00 AM, it's definitely time for morning coffee. When I get back, a note from my boss glares at me from the seat of my swivel chair. ("Call me. Dave W.")

I call up Dave W. on the telephone. "Did you read the MAIL I sent you?" he asks.

"No, I didn't hook up to the network yet."

"Okay, look. Read the MAIL, then see Leo. He wants you to do a worst case throughput analysis on the image processor, and see how heavily loaded the CPU is. See what he wants. Then get back with me so we can figure a promise date for the work."

"Okay." I hang up, and run the terminal emulation program on my PC, and sign on to the VAX®. (My PC is connected to a terminal server on the Ethernet® local-area network.) I read Dave W.'s MAIL, check the latest junk on the bulletin board, log out, and polish off my (by now cold) coffee. It's depressing how quickly hot coffee gets cold...

I walk over a few bays to see Leo, the technical manager for the imaging project. He wants me to study the system specifications and analyze the results of simulations run by the prime contractor (we're a subcontractor on this project); perform a loading analysis on two of the CPU's and their interface bus; and determine whether or not the current design will meet the specification. (If it doesn't, it may mean going back to the drawing board. Bad news, since it would cut into our profit. The margin is already slim on this job.) He also suggests that I see Larry, who worked with our prime during the proposal.

Larry is very helpful. He hands me a data package roughly a foot high. "Here you go, Dave. Good luck. The stuff you need is in there, somewhere. It's scattered around, though, and some of the stuff you're going to need isn't there."
"Great."
"Yeah, isn't it? Well, good luck. Give me a yell if you need help."
I carefully maneuver the metastable stack to my quad, drop the documents onto my work table, and browse through them. The system is extremely complex, with hundreds of functional modules, and I'm still "low on the learning curve". It will take some time for me to get up to speed. Mary complains about the "scatter" of data as well. She's been assigned to the project too, though Bill has been spared.

Two hours later, I know that Larry was right. It looks like I need to search for more information. At least half of the prime item development specs (PIDS) are missing from the data package, and some of the simulation results are a little hard to read given the poor copies. Well, at least it's better than the old blueprints. Maybe I'm showing my age. (I wonder if I still remember how to run the blueline copier? It was one of the first things they taught me how to run here, just in case I needed to run a blueprint copy late at night, when no one else was around to help me.)

I put together a work estimate for a "quick and dirty" worst case analysis (2 man weeks), and one based on developing a new simulation model of the system (8 man weeks). The short analysis uses some data from previous simulations on a similiar program. The numbers won't be exact (what simulation is?), but would be "pretty close", and save a considerable amount of time and money. I'm fairly sure Leo will go for the shorter alternative, since we're trying to save both. We'll get our best data from a full simulation, though, so I give Dave W. a call and push the 8-week job. Dave W. calls Leo, and they agree to meet before lunch.

Company 1 is run using matrix management, you see. Dave W. is my "functional manager". Leo is the "project leader". The two will negotiate for a "statement of work", a semi-formal description of what the Project Office wants from me (a "deliverable"), and a "schedule" (also a budget, since the schedule says how long I have to complete the work, at my standard pay grade, with standard management overhead). Some of the functional and project managers around here go into these negotiations like roosters in a cockfight. Dave W. and Leo are a bit calmer about it, though, and I get a pleasant surprise. Although I *am* asked to do a "rush" job to get a *preliminary* answer in two weeks, we also get an additional *four* man-weeks to perform a "limited simulation" comparing the two most promising alternatives. I would have preferred a little more time, but at least the job doesn't look impossible. It's probably going to involve a few late nights, though... I also take the opportunity to confirm my interview with Dave W. for later in the afternoon.

There's still a little time left before lunch, so I hunt around for the "missing" specs. I eventually find them by rummaging around in "stacks" of the program management office's library; I read another document in "the Tank", a special-projects area. By the time I've finished finding the information, it's time for lunch. (Our "official" lunch hour is 12:15 - 1:00. It's only 12:00 but my friends and I are all hungry, so it's off to the cafeteria, in bold defiance of Company guidelines.)

After lunch, I wander over to the conference room we're using as a project work area. There are a lot of engineers crammed in here, elbow to elbow, clicking madly away at a bunch of networked Macs. I find an older Mac free. Why this gift horse? The other Macs are much newer models, with the characteristic platinum coloration. This one is beige. Ah yes. This is a Mac 512. Old. Oldest one in the firm. Veteran of many proposal efforts. I turn on the hard drive, then the computer. A happy Mac face appears on the screen. Bong. And then the screen snaps, then comes back to life. It seems to do this once every five minutes or so. Hmm. Perhaps this is fitting. I own one of the oldest PC's in house. Now, I get to work on the oldest Mac in the house. How fitting! Wink. There went the screen again. Definitely a hardware fault. I wander down to the calibration lab to report a sick Mac, then return to conference room. Just my luck. It's still the only open Mac in sight... I had hoped... Ah, well. I click the mouse and get to work. Now, I wonder which Mac has the current B-Spec on it? Last week, it was on Ken's Mac...

Time to interview another manager. Today it's Dave W., the systems engineering manager and my functional boss. I proceed down the labyrinth of corridors to his office, and knock. "Dave?"

He looks up at me. "Come on in. I'll be with you in a moment." He finishes scribbling on a memo and puts the completed message in his outgoing box for Maureen to pick up. He pushes his chairback up, pushes his eyeglasses back up his nose, and asks, "Okay. What do you want to interview me about?"

"Well, Dave, how do you feel about your engineers using computers?"

He thinks a moment, and says, "You know, it's interesting that you ask that. I've been doing a lot of thinking about that lately. I know that in certain areas of engineering, like CAD or silicon compilers, you can get a lot more productive with computer tools. I've seen it for myself with the Applicon® systems we've got in house, and some of the gate array development systems at the Labs. But I'm ambivalent about how effective they are for the kind of work we do."

"What do you mean?"

"Well, let's get specific. You and Bill have been real lead users of PC's and laptops here, and have been very active in the Boston Computer Society and other groups. And you've been using computers a lot in your work."

"That's true."

"Well, one the one hand, you and Bill have produced a lot more studies in any given amount of time. I find it amazing how quickly you two can turn around and crank out another study. But I find the work you two have been doing a little disappointing." He hurriedly adds, "Now, don't take this as a criticism. Like I said, your productivity has gone up quite a bit. But, on the other hand... Well, you and Bill used to do a lot more figures, charts, and sketches when you used to do it by hand. And each analysis was fresh, from scratch. Each analysis you two did addressed the problem at hand."

"Well, Dave, maybe we don't have the right tools. I don't have very good drawing tools on my PC and laptop; I know Bill doesn't have a lot of capability on his laptops, either. If we had a Mac, we could do more pictures."
"That may be, but I think it goes deeper than that. When you do things by computer, you tend to re-use a lot of old material. It's how you save time, and gain your productivity improvement. But in our end of work, old solutions to problems may not be optimal solutions. On top of that, analysis work has very broad bandwidth. There's a lot of 'left brain' stuff that goes into problem solving. I don't think computer tools today offer the kind of breadth you need for this kind of work. It does cut and paste well, but doesn't support creativity very well."
"That's an interesting comment, Dave. Certainly food for thought..."

A.2. Backgrounds of Company 1 Engineers.

The background data frequencies shown in this section reflect responses provided by 92 Company 1 engineers in response to an Internal Mail distribution of the Questionnaire shown during 1987 and 1988. 49% of the engineers responded twice (once each year); their responses were aggregated by engineer to provide equal weight to each engineer participating in the study.

(Please answer all questions and return to me in the envelope provided. You are under no obligation to answer or return this questionnaire. All responses will be kept strictly confidential. No shop order is available. Study conducted by D Murotake x3812.)

1. **JOB:** What is your primary work responsibility? (check one)

26%___Electrical Engineering
23%___Software Engineering
20%___Mechanical Engineering
12%___Systems Engineering
03%___Project Management
07%___Engineering Management

07%___Other (specify: ______________________________)

2. **TECHNICAL EXPERIENCE:** Please check all areas in which you have at least ONE YEAR OF WORK EXPERIENCE (do not count school).

55%___Electrical Engineering
40%___Software Engineering /Computer Science
32%___Mechanical Engineering
30%___System Engineering
______Other Engineering
______Other Science/Math
19%___Management/Marketing
______Government/Military
22%___Other (____________)

3. **FORMAL EDUCATION:** Please indicate, in the blanks below, the highest academic degree obtained in each field (or its military/government equivalent) using the following code:

0=N/A 1=Associate 2=Bachelors 3=Masters 4=Doctorates

______Electrical Engineering
______Software Engineering /Computer Science
______Mechanical Engineering
______System Engineering
______Other Engineering
______Other Science/Math
______Management/Marketing
______Government/Military
______Other (____________)

4. **POSITION TITLE:** What is your current job title?____________________

05%___Technical 1   32%___Technical 2   21%___Technical 3

07%___Technical 4   15%___Technical 5   06%___Technical 6

16%___Management

5. **GENDER:** 91%___Male   09%___Female

6. Do you use computers in your work? 94%___Yes 06%___No
Do you feel user training is adequate? 58%___Yes 42%___No ______N/A
What system(s) do you use? (check all that apply)

55%_PC/Clone/ Macintosh
82%___Mini/Mainframe
05%___Laptop/Portable
12%___Workstation (Apollo Sun etc)
19%___Other (________)

7. **HIGH LEVEL LANGUAGES:** Which of these computer languages can you use with some proficiency? (check all that apply)

19%___ADA   71%___BASIC   19%___C   74%___FORTRAN
10%___LISP   51%___PASCAL   10%___PL-1   04%___PROLOG

20%___Other (Specify: ______________________________)

8. LOW LEVEL LANGUAGES: Have you done any "machine-level" programming? (check all that apply)

55%___Machine language   63%___Calculators, instruments, etc.
51%___Assembly language   55%___N/A

9. OPERATING SYSTEMS: Which operating systems have you used?

16%___UNIX & derivatives   45%___PC-DOS/MS-DOS/OS-2
82%___VAX VMS & derivatives   36%___Other (How many?_Avg=1_)

Do you do systems programming? (E.g. C/Unix)   ______Yes   ______No

10. HOME COMPUTERS:
Do you have a one or more?   54%___Yes   46%___No
Is it compatible with a computer at work?   23%___Yes   31%___No

11. TECHNICAL WORK AT HOME: Do you do any job-related technical work at home? (Check all categories that apply)

37%___Yes   60%___No   03%___N/A

Do you use your home computer for this work?   18%___Yes   19%___No

Can you access your computer files at work from home? (E.g. using a modem and phone)   ______Yes   ______No

12. COMMUNICATION: Do computer tools improve your communication with other engineers and managers:

WITHIN your project team or group?   25%___Yes   58%___No   17%___Unsure
EXTERNAL TO your project team or group?   ______Yes   ______No   ______Unsure

Are you a regular user of electronic mail?   52%___Yes   39%___No

13. SCOPE OF WORK: In some fields, computer tools enable the professional to do work which couldn't be done manually. Is this true in your case?

57%___Yes   34%___No   10%___Unsure

14. QUALITY OF WORKING LIFE: What overall effect (if any) have computer tools had on the quality of your life as pertaining to, or affected by, your job? (Check one)

52%___Mostly better   26%___About same   02%___Mostly worse   10%___Unsure

Have computer tools made your life better/easier in any way? If so, please explain:

25%___Yes w/answer   00%___No w/answer   75%___No Answer

Have computer tools made your life worse/harder in any way? If so, please explain:

17%___Yes w/answer   02%___No w/answer   80%___No Answer

A.3. Engineering Projects at Company 1.

The data frequencies shown in this section reflect responses provided by 21 Company 1 project managers in response to an internal mail distribution of the Questionnaire shown. Just over half of the projects at Company 1 for which survey responses were returned were small (52%) projects with government-funding (86%). Most of the remaining projects were of moderate size (38% between 6-50 engineers), although there were two large projects with over 50 members. The "typical" project was a full-scale development project (43%) requiring the acquisition or development of new technologies (71%), perceived by the project manager to be fully staffed (76%) by moderately loaded engineers (38%), doing non-developmental (52%), moderate-quality work (95%) which was on budget (57%) and on schedule (52%). Frequencies of responses provided by Company 1 managers in response to the questionnaire are shown below:

---

*Please answer **both parts** of this questionnaire. You are under **no obligation** to answer this questionnaire. There is no shop order for time spent in filling out this questionnaire.*

I. PROJECT CHARACTERISTICS

1. **SIZE.** How many people are currently involved in this project?

11 (.52) 1-5 4 (.19) 6-10 0 (.00) 11-20 4 (.19) 21-50 2 (.10) 51+

2. **FUNDING.** What is the source of the project's funding?

18 (.86) Government
04 (.19) Company funds
______ Research & Development
______ Production
______ Other

3. **DURATION.** How old is this project?

11 (.52) 0-1 year (1988)
06 (.29) 1-2 years (1987)
______ 2-3 years (1986)
______ 3-4 years (1985)
01 (.05) 5+ years (1984)
03 (.14) No Answer

4. **TECHNOLOGY.** Please indicate the technology requirements for successful project completion. *Technology* can include both *products* (such as H/W or S/W) and *processes* (such as a requirements definition methodology, quality inspection technique, or manufacturing process).

6 (.29) a. This project requires only that technology which we already had in-house.
6 (.29) b. This project requires technology which we didn't originally have in-house,but which we can procure on-the-shelf from a vendor, another division or corporate lab, etc.
9 (.43) c. This project requires the development of new technology - that is, technology which we don't have in-house, and which we are unable to procure from another source. (This category also covers *reverse engineering* of products or processes.)

5. **PHASE.** What is the current project phase? (Place an 'X' on the line above current phase.)

2 (.10) PreProposal /IR&D
3 (.14) Proposal
1 (.05) Prelim Design/Develop
9 (.43) Full-Scale Develop
3 (.14) Production
2 (.10) Maintenace & Prod Improve
1 (.05) No answer

6. **MANNING.** What is the manning status of your project? 05 (.24) Understaffed.
16 (.76) Fully staffed.

7. **WORK LOAD.** Please characterize the ***average*** work load of engineers working on your project during the **past three months**:

10 (.48) 3. Their work load is **heavy**, leaving little time to keep up with professional reading, etc.
08 (.38) 2. Their work load is **moderate**, leaving some time for professional reading, etc.
03 (.14) 1. Their work load is **light**, leaving considerable time for professional reading, etc.

8. **INNOVATION.**
11 (.52) 1. Non-developmental
09 (.43) 2.
01 (.05) 3. Highly innovative

9. **QUALITY.**
______ 1. Lower
20 (.95) 2.
01 (.05) 3. Higher

10. **BUDGET.**
04 (.19) 1. Under budget
12 (.57) 2.
04 (.19) 3. Over budget

11. **SCHEDULE.**
10 (.48) 1. Behind
11 (.52) 2.
______ 3. Ahead

A.4. Availability of Computer Tools at Company 1.

Figure A-1 shows the computer system available for use by engineers at Company 1. The heart of the system is a cluster of high performance minicomputers, networked by a local area network. The minicomputers provide a number of services to timesharing account holders, ranging from simple editors and electronic mail systems to sophisticated programming tools and CAD systems. In fact, several of the site's CAD workstations use the minicomputers as file servers and print servers over the network. Ownership of the minicomputers is territorial, with each engineering subsection "owning" one or more machines. The network itself is "owned" by the Company 2 engineering section.

Access to the minicomputers is via video terminals and terminal servers hooked to one of several local area networks. Terminals are numerous, are distributed as follows: one per one-man bay, and two per four-man bay. Personal computers are also common, the ratio being about one PC per two engineers. About one third of the engineers have their own PC's, while other PC's are networked to laser printers and other specialized hardware in section or group work clusters.

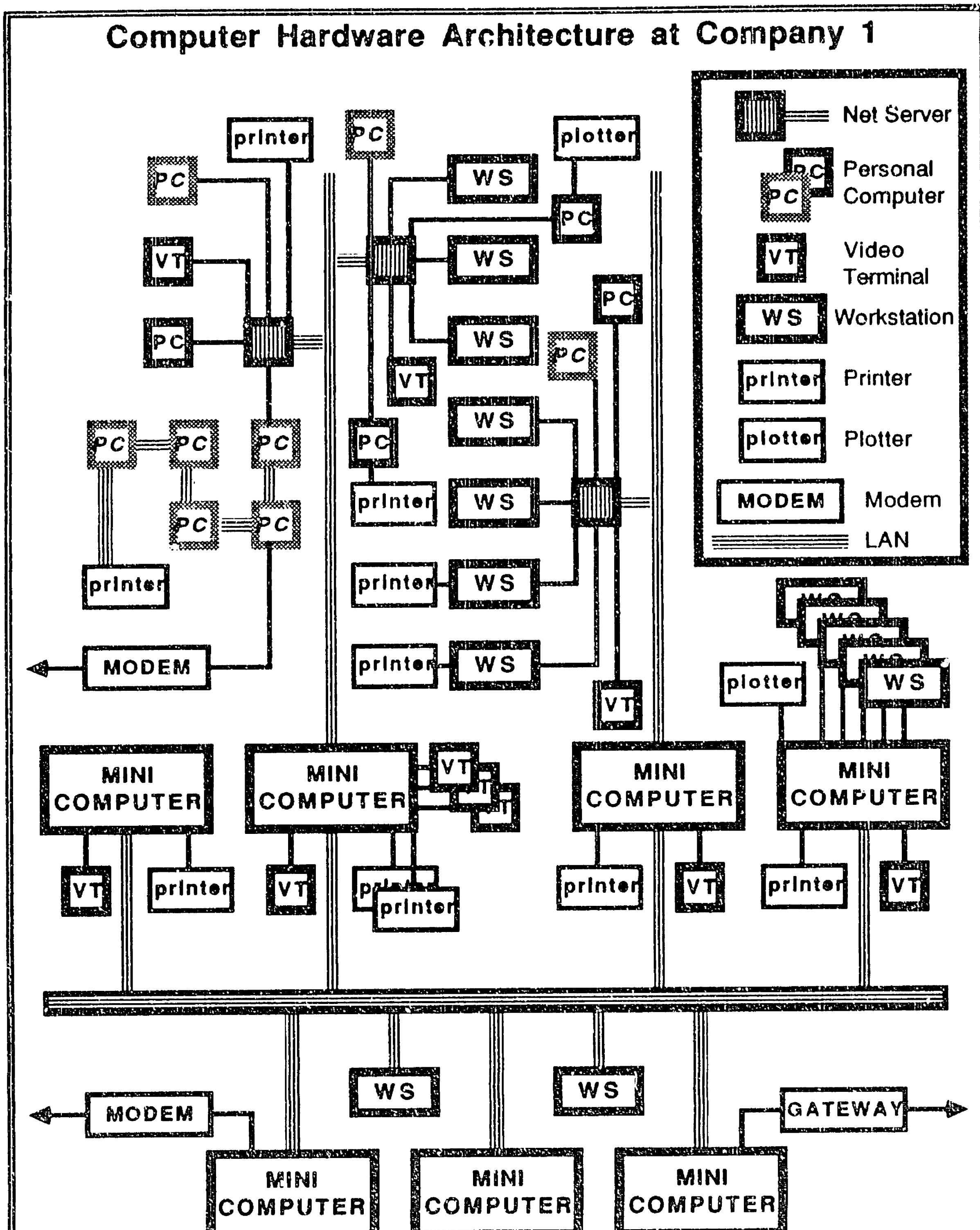

Figure A-1. Computer hardware system at Company 1, consisting of networked minicomputers, CAD workstations, and personal computers. Most machines are stand-alone, with electronic mail, limited file transfer, and timeshared minicomputer access provided by the network. (1988)

Figure A-2 shows the intercorrelations of hardware tools reported as accessible by Company 1 engineers. Data for reported hardware availability was correlated using a Spearman rank-order correlation to show what kinds of hardware tended to "show up together." Correlations shown are all substantially correlated (|R| > .40) at the (p < .01) level of significance. Note, for instance, the cluster of minicomputer, input device, workstation, printer/plotter, and network on the left-hand side. This reflects the use of CAD workstations, equipped with mice, using the minicomputers as file servers and print servers over the network. Terminals and PC's were ubiquitous, and were not strongly correlated with other hardware. All substantial correlations were positive.

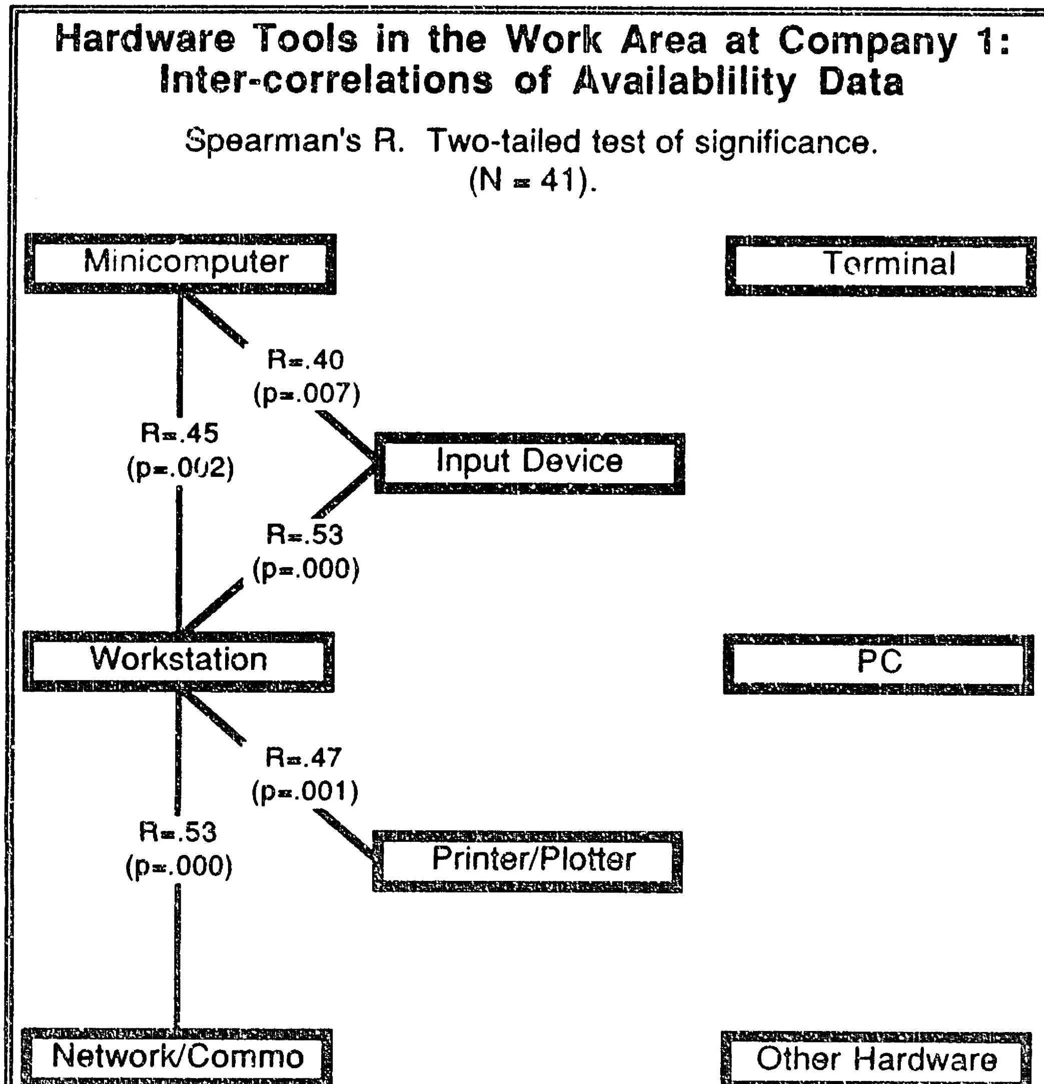

Figure A-2. Intercorrelations of hardware tool accessibility in the primary work area, as reported by engineers of Company 1. Workstations at this facility generally used minicomputers as both file and print servers via the network. (1988)

Figure A-3 shows the intercorrelations of software tools reported as accessible by Company 1 engineers. Data for reported software availability was intercorrelated using a Spearman rank-order correlation. There was one strong correlation ($R = .78$) at the ($p = .000$) level of significance between drawing tool availability and spreadsheets. (Note: Spreadsheet s used at Company 1 generally have integrated graphics packages, used to generate charts. Charts generated on spreadsheets are then imported into drawing programs for editing prior to final use.) There are numerous other correlations shown. All are substantially and positively correlated ($R > +.40$) at the ($p < .006$) level of significance.

Software Tools in the Work Area at Company 1: Inter-correlations of Availability Data

Spearman's R. Two-tailed test of significance.
(N = 41).

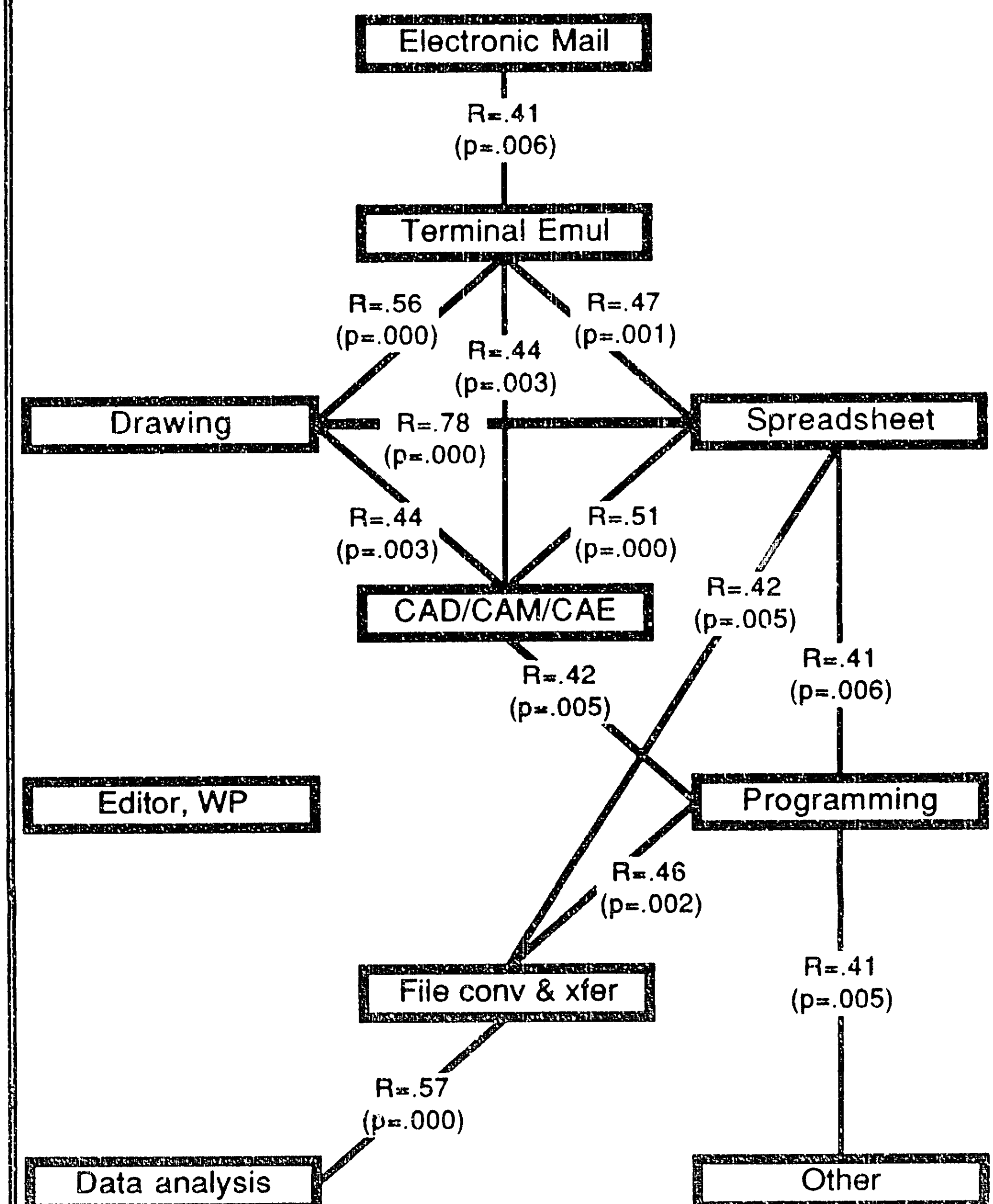

Figure A-3. Intercorrelations of software tool availablity as reported by engineers of Company 1.

A.5. Utilization of Computer Tools at Company 1.

Engineers make extensive use of computer tools at Company 1 to perform a wide range of tasks. Of the 7.64 hours per day spent working on the two most time-consuming projects, 3.62 hours (42%) were spent using computer tools (Table A-1). Writing (n=19), meeting attendance (n=18), and searching for information (n=10) were the tasks most frequently performed by the 41 Company 1 engineers providing computer use information. Computers were used by the majority of engineers performing certain tasks, such as writing (16/19), software development (7/9), and problem identification (6/8). Although use of computers for software design and development come as no surprise, the use of computers to support almost all categories of engineering work is widespread.

Task Type	Avg Hrs Total	Avg Hrs w/Comp	Std Dev w/Comp	Comp Use %	Perform Task	Used Comp	Comp User %
Market Analysis	0.07	0.00	0.00	0.00	3	0	0.00
Requirements Analysis	0.11	0.02	0.10	0.13	3	1	0.33
Technology Scanning	0.03	0.00	0.00	0.00	2	0	0.00
Problem Identification	0.46	0.23	0.71	0.50	8	6	0.75
Idea Generation	0.10	0.02	0.10	0.15	6	1	0.17
Experimentation	0.00	0.00	0.00	—	0	0	—
Mathematical Analysis	0.02	0.02	0.15	1.00	1	1	1.00
Modeling & Simulation	0.01	0.00	0.00	0.00	1	0	0.00
Trade Study	0.05	0.00	0.00	0.00	2	0	0.00
Cost Analysis	0.42	0.19	1.00	0.46	7	3	0.43
System Design	0.35	0.09	0.60	0.26	5	1	0.20
Mechanical Design	0.13	0.00	0.00	0.00	3	0	0.00
Electrical Design	0.15	0.03	0.18	0.18	5	2	0.40
Software Design	0.34	0.23	1.08	0.67	3	2	0.67
Mechanical Development	0.05	0.00	0.00	0.00	1	0	0.00
Electrical Development	0.13	0.05	0.24	0.34	3	2	0.67
Software Development	0.72	0.46	1.29	0.63	9	7	0.78
System Integration & Test	0.52	0.44	1.54	0.85	6	5	0.83
Production Engineering	0.31	0.06	0.40	0.20	2	1	0.50
Quality Control	0.01	0.01	0.08	1.00	1	1	1.00
Maint & Troubleshooting	0.73	0.34	1.18	0.46	7	5	0.71
Writing & Editing	1.25	0.75	1.35	0.60	19	16	0.84
Drafting & Drawing	0.07	0.03	0.12	0.39	4	2	0.50
Searching for Information	0.33	0.09	0.33	0.28	10	5	0.50
Reading	0.06	0.01	0.04	0.08	6	1	0.17
Meetings	0.72	0.09	0.53	0.12	18	2	0.11
Briefings & Preparation	0.16	0.08	0.37	0.54	7	5	0.71
Training & Education	0.00	0.00	0.00	—	0	0	—
Project Management	0.18	0.01	0.05	0.04	5	1	0.20
Group Management	0.09	0.00	0.00	0.00	2	0	0.00
System Management	0.00	0.00	0.00	—	0	0	—
Other	0.07	0.00	0.00	0.00	2	0	0.00
TOTAL	7.64	3.22	11.44	0.42			

Table A-1. Summary data for computer tool utilization at Company 1 for 44 participating engineers during 1988.

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APPENDIX B. Company 2.

B.1. Impressions of a Researcher at Company 2.

It's hard for me to be dispassionate when I describe Company 2. I know I have my responsibilities, as a professional, cooly objective researcher, but... It's still damnably hard for me to talk about this place without sounding like a salesman, or worse yet, a *marketeer* (that arch-villain to all *real* engineers!)

Let me, in my own stumbling (!) way, seal my doom by attempting to define something called *technical culture*. It's the way a technical organization, like an engineering firm or a scientific lab, does things. It's a combination of work environment, policies and procedures, technologies available to do things...

Company 2 builds workstations. And networks. And operating systems. And computer tools. It also evaluates computer tools made by other companies, and (assuming it wasn't made by a competitor with a three-lettered name!) integrates the best of these applications into their workstation *environment*.

Nor is this place plagued by the "shoemaker's son syndrome." (As the story went, the cobbler was so busy selling shoes to the town, that the only ones with tatty shoes were members of his own family...) You see, everybody at Company 2 seems to have a *node*. A node is more than "just a workstation", it's a workstation with *connectivity* to a vast network of workstations, file servers, print servers, and more. At most other engineering companies, you can almost measure an engineer's status by whether he has a PC or not. At Company 2, the yardstick is more the speed of the workstation, the version of the operating system, the size and resolution of the monitor, and the number of accessible applications.

Clicking mice seems to be a passion around here. Everybody (well, almost everybody; some prefer touch pads, while touch-typists don't like to use anything which takes your hand off the keyboard...) clicks mice around here. They run a truly paperless office... Secretaries and receptionists send memos and phone messages to their boss via Email window. The *phone book* is on the network. Everyone has a workstation. Everyone. Engineers, secretaries, managers, marketeers, network specialists, security guards.

An engineer named Dan gets to be my mentor. Dan is an engineer with the CAE Tools group, and is supposed to keep me out of trouble. He made sure I got an office, a workstation, a phone, a desk, and an EMail account (very important here!). He also made sure I knew where the restroom was (also very important!).

This is the kind of place most engineers just fantasize about. Most of us only dream about having a nice CAD workstation with all this software... Dan showed me to my new office, and there's this workstation there, you know? He showed me how to turn on the machine and log in. After copying the Startup file from his own Node, he turned the workstation (node Carnegie, my very own node!) over to me. By lunchtime, I was banging on his door with this big Cheshire-cat grin on my face. I feel like I'm in Nirvana. Over the next few weeks, I ran into an even half-dozen "new-hires" at Company 2, and they all seemed to have similiar experiences.

I'm afraid it took me more than a morning to get used to my "node". (Local legend says the node is named Carnegie because its first owner was fond of his alma mater, Carnegie-Mellon. Carnegie was an "older" workstation, signalling my low position on the pecking order). It took me a few days. I'd worked on UNIX machines before, and coded in C, but I wasn't quite prepared for the workstation's power (this is *really* on my desk??? I could run a dozen simultaneous jobs on this machine, each with its own "window" interface. I could sort a database, print a word processing file on the laser printer, download a file from another node, and read my electronic mail at the same time.).

The network and its distributed computing environment also took some getting used to. If I logged on to my node while physically at the workstation, the node was like a super PC with network connectivity. But I could also log on the network *at any workstation hooked to the network.* If my "home" node was hooked in, I got access to all the "local" files I had stored there. If not, I would log in as a fully privileged user, and have all network access and privileges, hosted as a "guest" on another node selected by the network.

They run a truly "paperless office" here, with extensive use of electronic mail, bulletin boards, and on-line databases (even the phone book is online!). Only two internal Company functions still use paper: legal work, and engineering change notices (which must be initialed by the responsible design managers). Most of the remaining paper is from, or for the "outside". Although I initially preferred hard copy to edit material, I quickly abandoned its use. On traditional video terminals and PC's, you get the equivalent of 25 lines of 80-column text display, about 40% of a full-sized sheet of paper. Since I like to be able to flip rapidly back and forth over several pages, I found this limited view frustrating. All this changed on the workstation! Having a large (19"), very high resolution display allowed me to have the equivalent of *two and a half* full-sized sheets of paper simultaneously displayed. By arranging windows so they overlapped, I could have literally dozens of "sheets" available at the click of a mouse. And the ever-present computer search ability eliminated the otherwise inevitable search through the desk-top, in/out boxes, file drawers, and other nooks and crannies of information storage.

The workstation, with its multi-window screen and network access to a wide range of applications (CAD, data bases, editors, etc.) was like having a half-dozen Macs or PC's working for you *all at the same time...* The horsepower is simply awesome. When engineers get into a piece of work that "hangs" (such as resorting a large data base, recomputing a net list, or transferring a large data file over the network), they simply click on another open window and do something else (such as read your electronic mail) while the other job "churns away".

I think I failed my first "social acceptability" test. On my first day, I got introduced to one of their software gurus. I got asked this string of questions. "Do you do UNIX?" "Yeah." "Code C?" "Sure..." "How about shell scripts, you do shell scripts?" "Doesn't everybody?" (Ah, so far, so good). "Gee, great! Are you a software hack?" "No, I'm a systems engineer." That's when I lost it, I think. I got this piercing stare, the glimmer of realization that I might *really* be from Mars, after all.... "A systems engineer?" (gulp) "Uh, yeah..." I could almost hear that next line: *Gee, that's too bad. My brother-in-law does that, too.* Or something to that effect.

It turned out that I needn't have worried. There were quite a few "systems" engineers working at Company 2. Some of them even lived in the area I did, although I often shared office space with new-hires, summer interns, and Co-op students. (Interns and co-ops are upperclass engineering undergraduates, doing practicum work with local engineering companies.) In one instance, a Co-op named Bruce had also done Co-op work at Company 1, and was very instrumental in pointing out some interesting differences - and similiarities - between the two sites. He had been at Company 1 for two years, and was just finishing up his second year at Company 2.

The paperless office environment gave me an interesting headache. My informants within the company recommended that I *not* use "hard-copy" questionnaires, since that was counter-cultural. Instead, I was to develop some *electronic* form of the questionnaire, in a format that would be unobtrusive to the majority of engineers at the site. The notion of using a data base of some form to generate questionnaires, collect responses, and code the data automatically was quite seductive, and I spent several weeks trying out different ways of doing that. In the end, though, I ended up using the EMail system to distribute, and collect, questionnaires as simple "text" files, a format which is compatible with almost all computer systems, including the IBM-PC®'s and Apple Macintoshes® I would be using for some of my data entry and data manipulation.

Once I had formatted, pretested, and modified the electronic form of the research instruments I had used at Company 1, I then fell into a two-day-per-week routine of working at Company 2. I would come in to work (somewhere around 9 AM; employees would come to work somewhere between 7:30 AM and 9:30 AM), log on to my node and generate the appropriate random sample of questionnaires to be distributed that day. I would mail out the questionnaires over EMail, and then browse my mail for incoming messages (and returned questionnaires from previous sessions). It's amazing what's on the EMail. There's junk mail, section and project team notices, clipping services on the "Competition" and what they're doing, personal mail, and (hurray!) returned questionnaires. The returned questionnaires get copied to a response file, and copied to IBM-PC compatible floppies at the end of the day. Often, the questionnaire comes back with questions and comments. These I answer immediately. (Conveniently, the EMail system has a "respond" feature, allowing me to automatically send mail to the author of the letter I'm reading at the time.)

During the summer, I went on a two-week vacation over the Fourth of July. Company 2's R&D group had moved down the hill to a (much larger) new building while I was gone. So on my first day back from vacation, I was lost. Or rather, my node (and office) was lost. After Dan and I hunted around for it for a few minutes, I found an empty node, sat down at it, and logged on. (I can log in on any physical node on the network, and I get logically linked to my "home" node.) Yep, Carnegie's on the node. So it didn't get packed up and sent into cold storage. Good news. I then format a quick note on junk mail for wide distribution. "Hello, Junkers! Help, I'm lost..." Quickly outlining my tale of woe, I send out my plea for help out on the net. And in minutes, I'm answered. Some very inventive "Junker" (junk mail reader) has figured out which network loop I'm on, found the upstream node from my lost Carnegie, and found an active User on that node. Using PI (Phone Information, the electronic phone book) he finds out the phone number and address of the upstream user. Dan drops by a couple of minutes later. He recognizes the name. "Yeah, he's even in our group!". We march two hallways down, find his office, and look next door. There it is. Long lost Carnegie. (Well, only lost for fifteen minutes.) I couldn't have found a lost node this quickly at Company 1...

B.2. Backgrounds of Company 2 Engineers.

The background data frequencies shown in this section reflect responses provided by 24 Company 2 engineers in response to an electronic mail distribution of the Questionnaire shown:

ENGINEERING SURVEY: COMPUTERS AND WORK

1. JOB: What is your primary work responsibility? (check one)

______Electrical Engineering
67%___Software Engineering
______Mechanical Engineering
______Systems Engineering
08%___Project Management
21%___Engineering Management

04%___Other (specify: ______________________________)

2. TECHNICAL EXPERIENCE: Please check all areas in which you have at least ONE YEAR OF WORK EXPERIENCE (do not count school).

30%___Electrical Engineering
96%___Software Engineering /Computer Science
04%___Mechanical Engineering
33%___System Engineering
______Other Engineering
______Other Science/Math
33%___Management/Marketing
______Government/Military
42%___Other (______________)

3. FORMAL EDUCATION: Please indicate, in the blanks below, the highest academic degree obtained in each field (or its military/government equivalent) using the following code:

0=N/A 1=Associate 2=Bachelors 3=Masters 4=Doctorates

______Electrical Engineering
______Software Engineering /Computer Science
______Mechanical Engineering
______System Engineering
______Other Engineering
______Other Science/Math
______Management/Marketing
______Government/Military
______Other (______________)

4. POSITION TITLE: What is your current job title?____________________

00%___Technical 1 04%___Technical 2 46%___Technical 3
04%___Technical 4 08%___Technical 5 08%___Technical 6

30%___Management

5. GENDER: 87%___Male 13%___Female

6. Do you use computers in your work? 100%___Yes 00%___No
Do you feel user training is adequate? 75%___Yes 08%___No 17%___N/A
What system(s) do you use? (check all that apply)

13%___PC/Clone ______Mini/Mainframe 100%___Workstation (Apollo Sun etc)
_____Macintosh ______Laptop/Portable 04%___Other (________)

7. HIGH LEVEL LANGUAGES: Which of these computer languages can you use with some proficiency? (check all that apply)

17%___ADA 54%___BASIC 75%___C 75%___FORTRAN
25%___LISP 88%___PASCAL 38%___PL-1 17%___PROLOG

25%___Other (Specify: ______________________________)

8. LOW LEVEL LANGUAGES: Have you done any "machine-level" programming? (check all that apply)

58% ___Machine language
92% ___Assembly language
25% ___Calculators, instruments, etc.
04% ___N/A

9. OPERATING SYSTEMS: Which operating systems have you used?

88% ___UNIX & derivatives
71% ___VAX VMS & derivatives
46% ___PC-DOS/MS-DOS/OS-2
70% ___Other (How many? Avg=3)

Do you do systems programming? (E.g. C/Unix) ______Yes ______No

10. HOME COMPUTERS:

Do you have a one or more? 42% ___Yes 54% ___No
Is it compatible with a computer at work? 21% ___Yes 33% ___No

11. TECHNICAL WORK AT HOME: Do you do any job-related technical work at home? (Check all categories that apply)

67% ___Yes 29% ___No 04% ___N/A

Do you use your home computer for this work? 33% ___Yes 33% ___No

Can you access your computer files at work from home? (E.g. using a modem and phone) ______Yes ______No

12. COMMUNICATION: Do computer tools improve your communication with other engineers and managers:

WITHIN your project team or group? 92% ___Yes 08% ___No ______Unsure
EXTERNAL TO your project team or group? ______Yes ______No ______Unsure

Are you a regular user of electronic mail? 100% ___Yes 00% ___No

13. SCOPE OF WORK: In some fields, computer tools enable the professional to do work which couldn't be done manually. Is this true in your case?

92% ___Yes 04% ___No 04% ___Unsure

14. QUALITY OF WORKING LIFE: What overall effect (if any) have computer tools had on the quality of your life as pertaining to, or affected by, your job? (Check one)

96% ___Mostly better 04% ___About same 00% ___Mostly worse 00% ___Unsure

Have computer tools made your life better/easier in any way? If so, please explain:

71% ___Positive 00% ___Negative 30% ___No Answer

Have computer tools made your life worse/harder in any way? If so, please explain:

38% ___Positive 08% ___Negative 54% ___No Answer

B.3. Engineering Projects at Company 2.

The data frequencies shown in this section reflect responses provided by 11 Company 2 project managers in response to an electronic mail distribution of the Questionnaire shown in Figures C-5 and C-6 of Appendix C.:Most projects at Company 2 for which survey responses were returned were small (82%), company-funded (73%) projects, although there were two larger projects with 6-20 members. The "typical" project was a full-scale development project (29%) requiring the development of new technologies (64%), perceived by the project manager to be understaffed (55%) by heavily worked engineers (73%), doing innovative, high-quality work which was both overbudget and behind schedule. Frequencies of responses provided by Company 2 managers in response to the questionnaire are shown below:

---

*Please answer **both parts** of this questionnaire. You are under **no obligation** to answer this questionnaire. There is no shop order for time spent in filling out this questionnaire.*

I. PROJECT CHARACTERISTICS

1. SIZE. How many people are currently involved in this project?

9 (.82) 1-5   1 (.09) 6-10   1 (.09) 11-20   ______21-50   ______51+

2. FUNDING. What is the source of the project's funding?

______Government   8 (.73) R & D (Company-funded Engineering)
6 (.55) Company funds   ______Production
______Other

3. DURATION. How old is this project?

4 (.36) 0-1 year (1988)
3 (.27) 1-2 years (1987)
2 (.18) 2-3 years (1986)
1 (.09) 3-4 years (1985)
1 (.09) 5+ years (1984)

4. TECHNOLOGY. Please indicate the technology requirements for successful project completion. *Technology* can include both *products* (such as H/W or S/W) and *processes* (such as a requirements definition methodology, quality inspection technique, or manufacturing process).

2 (.18) a. This project requires only that technology which we already had in-house.
2 (.18) b. This project requires technology which we didn't originally have in-house,but which we can procure on-the-shelf from a vendor, another division or corporate lab, etc.
7 (.64) c. This project requires the development of new technology - that is, technology which we don't have in-house, and which we are unable to procure from another source. (This category also covers *reverse engineering* of products or processes.)

5. **PHASE.** What is the current project phase? (Place an 'X' on the line above current phase.)

_______PreProposal /IR&D
_______Proposal
2 (.18) Prelim Design/Develop
6 (.29) Full-Scale Develop
1 (.09) Production
2 (.18) Maintenace & Prod Improve

6. **MANNING.** What is the manning status of your project?

6 (.55) Understaffed.
4 (.36) Fully staffed.
1 (.09) No answer.

7. **WORK LOAD.** Please characterize the ***average*** work load of engineers working on your project during the **past three months**:

8 (.73) 3. Their work load is **heavy**, leaving little time to keep up with professional reading, etc.
2 (.18) 2. Their work load is **moderate**, leaving some time for professional reading, etc.
_______1. Their work load is **light**, leaving considerable time for professional reading, etc.
1 (.09) 9. No answer.

8. **INNOVATION.**
1 (.09) 1. Non-developmental.
5 (.45) 2.
5 (.45) 3. Highly innovative.

9. **QUALITY.**
_______1. Lower.
6 (.55) 2.
5 (.45) 3. Higher.

10. **BUDGET.**
2 (.18) 1. Under budget.
4 (.36) 2.
5 (.45) 3. Over budget.

11. **SCHEDULE.**
8 (.73) 1. Behind schedule.
2 (.18) 2.
1 (.09) 3. Ahead of schedule.

B.4. Computer Tool Availability at Company 2.

Figure B-1 shows the computer system available at Company 2. The computer system at this site is radically different from the system used at Company 1. The heart of this system is the engineering workstation (called a node), distributed one per engineer, manager, and secretary. Each node is capable of stand-alone operation if necessary, but is usually operated as part of a distributed computing environment consisting of many nodes and several hierarchies of network. Approximately a dozen nodes (a work group) are connected to a local network, on which are available file servers (with high capacity disks) and print servers (with laser printers, high speed line printers, plotters, etc.) This network, in turn, is part of a network of networks, which in turn can connect with other networks via high-capacity "bridges".

A user can sign on to his machine on any workstation logically connected to his "home" node by some network path; if connectivity to the home node is temporarily unavailable, the intelligent network signs the user on to some other physical node. Users have access to a large library of networked software applications, electronic mail and bulletin board services, and design data bases. Licensed applications can be used on any node through a "license server", which monitors startup and shutdown of licensed software, and provides accounting information for license payment purposes.

Personal computers can hook up to the network in several ways. The preferred method is via installation of a coprocessor card which allows the PC to function as a "node" on the network, with full network privileges. There are also coprocessor cards and external drives available for the workstations, allowing them to read and write PC diskettes, and run a wide variety of PC software (both hardware and software emulation are available). PC's are relatively uncommon at Company 2, their users apparently falling into three categories. These are: engineers developing specialized compatibility hardware and software for PC's; managers preferring to use PC tools such as spreadsheets or project planning software; and highly dedicated PC devotees (Mac hacks and the like...).

Users of mainframe computers and minicomputers fall into similiar categories. They are most often used by engineers in the development of specialized compatiblility products to permit their use in the networks of workstations produced by Company 2. They also serve as hosts for unique software applications which only run on special hardware. In at least one instance, an engineer used a university mainframe computer to support nonresident doctoral research. (I found a kindred spirit here! The engineer was pursuing a Ph.D. in computer sciences.)

Computer Hardware Architecture at Company 2

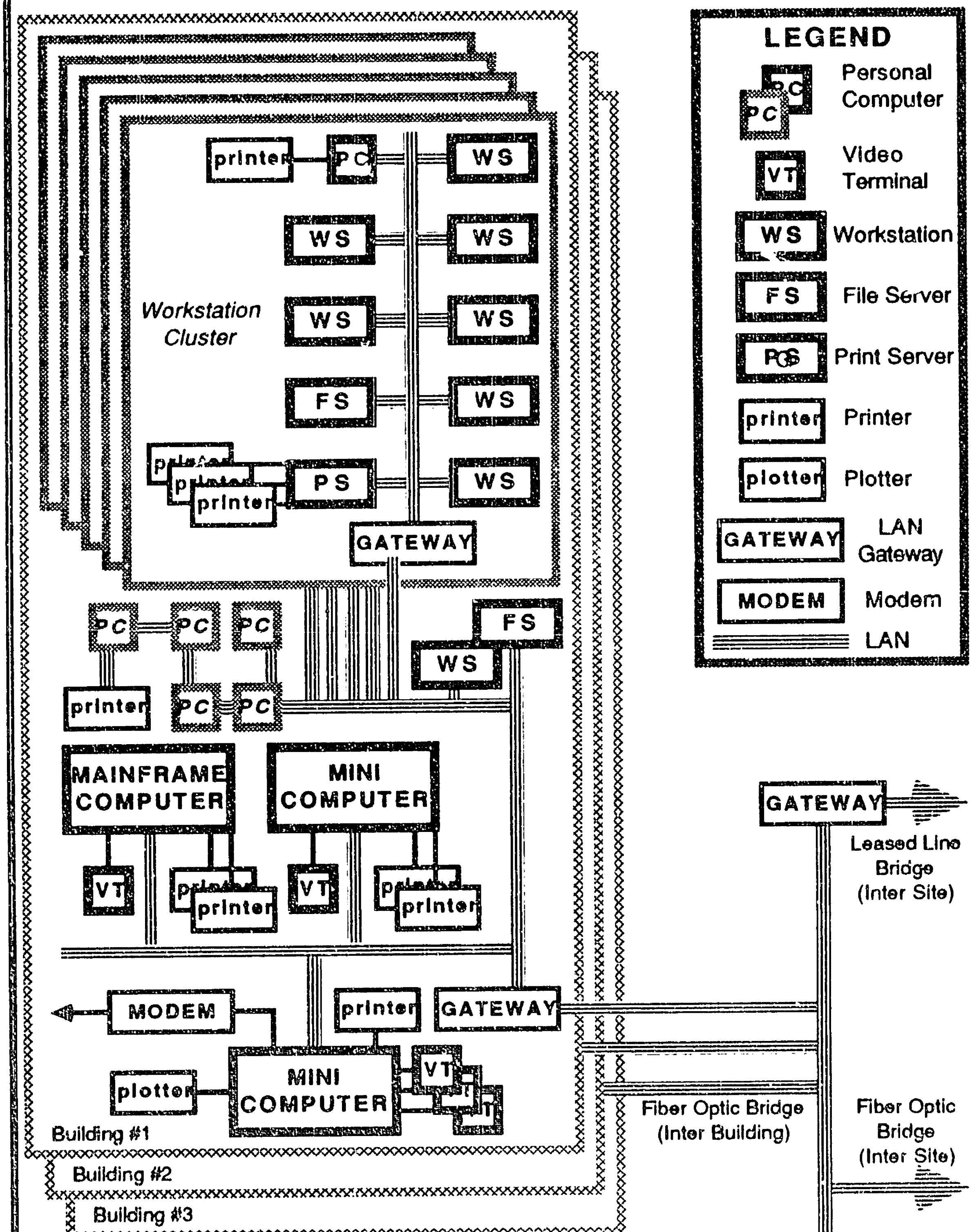

Figure B-1. Computer hardware system at Company 2, consisting of networked engineering workstations, file servers, print servers and other equipment. Networked applications, electronic mail, and graphics/design database sharing are available via the network. (1988)

Figure B-2 shows the intercorrelations of hardware tools reported as accessible by Company 2 engineers. Data for reported hardware availability was intercorrelated using a Spearman rank-order correlation to show what kinds of hardware tended to "show up together." Correlations shown are all substantially ($|R| > .40$), strongly ($|R| > .60$) or highly ($|R| > .80$) correlated at the ($p < .03$) level of significance. Note, for instance, the cluster of minicomputer, terminal, and mainframe in the upper-left hand corner. This cluster reflects the presence of "computer rooms" with mainframes, minicomputers, and terminals located nearby. (These are usually development labs for compatibility products.) Engineering workstations, equipped with mice and connected to print servers and other hardware over the network make up the other cluster in the bottom right-hand corner. All significant correlations were positive.

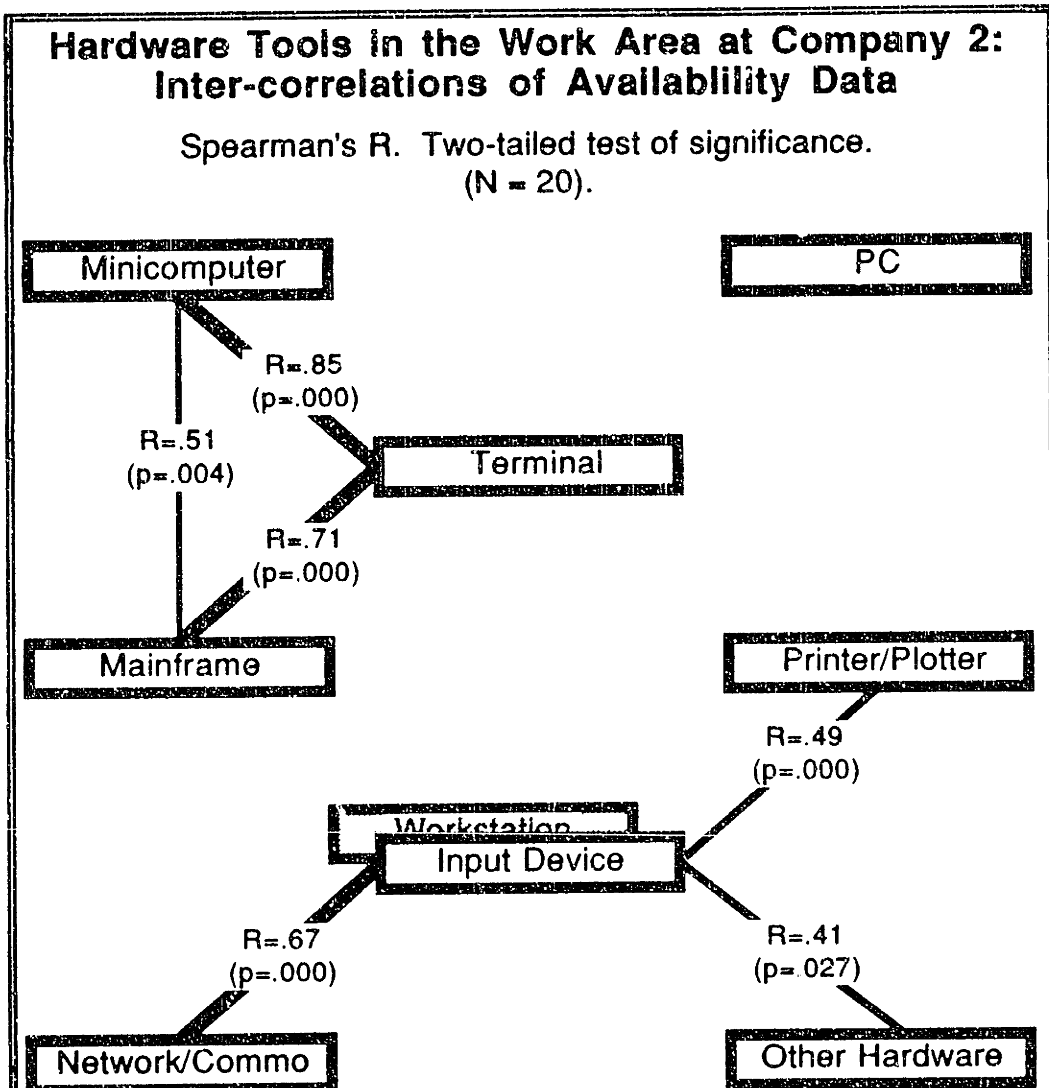

Figure B-2. Intercorrelations of hardware tool accessibility in the primary work area, as reported by engineers of Company 1. Workstations at this facility generally used minicomputers as both file and print servers via the network. (1988).

Figure B-3 shows the intercorrelations of software tools reported as accessible by Company 2 engineers. Data for reported software availability was intercorrelated using a Spearman rank-order correlation. There was one strong correlation (R=.69) at the (p = .00) level of significance between programming tools availability and editors/word processors. (Note: Although language-sensitive editors are generally part of any set of programming tools, programmers tend to develop a "favorite" editor, and tend to favor it for initial code generation, and final formatting of documented source code.) Numerous other correlations were present, all substantially and positively correlated (R > +.40) at the (p < .03) level of significance.

Software Tools in the Work Area at Company 2: Inter-correlations of Availability Data

Spearman's R. Two-tailed test of significance. (N = 20).

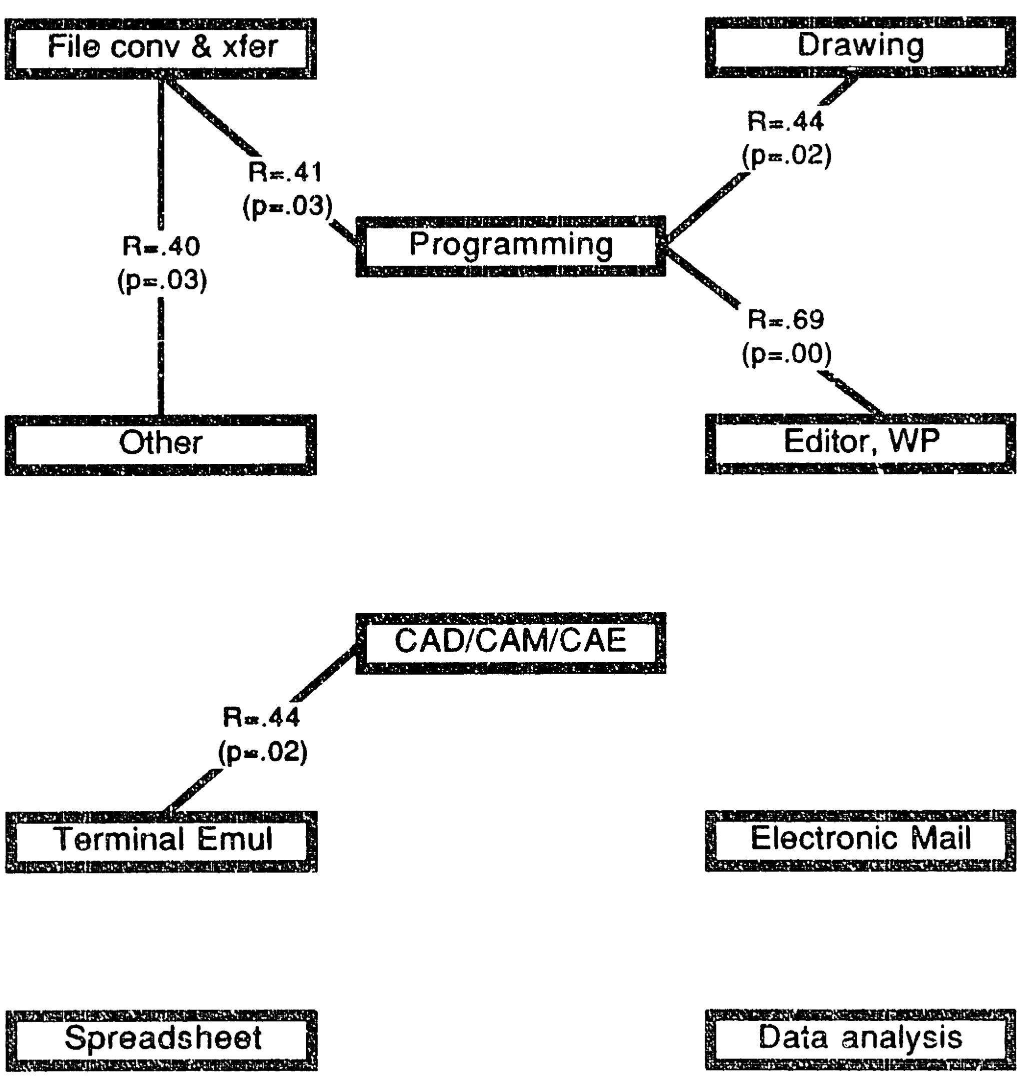

Figure B-3. Intercorrelations of software tool availablity as reported by engineers of Company 2. (1988)

B.5. Computer Tool Utilization at Company 2.

Engineers make extensive use of computer tools at Company 2 to perform most of their work. Of the 8.83 hours per day spent working on the two most time-consuming projects, 5.31 hours (60%, or half again as much as at Company 1) were spent using computer tools (Table B-1). Writing (n=20), meeting attendance (n=20), and reading (n=17) were the tasks most frequently performed by the 20 Company 2 engineers providing computer use data. Computers were used by the majority of engineers performing certain tasks, such as writing (20/20), software development (13/13), and reading (13/17).

Task Type	Avg Hrs Total	Avg Hrs w/Comp	Std Dev w/Comp	Comp Use %	Perform Task	Used Comp	Comp User %
Market Analysis	0.07	0.06	0.31	0.84	1	1	1.00
Requirements Analysis	0.03	0.02	0.09	0.53	3	1	0.33
Technology Scanning	0.23	0.12	0.56	0.53	5	2	0.40
Problem Identification	0.49	0.33	0.69	0.66	12	8	0.67
Idea Generation	0.51	0.24	0.49	0.47	13	8	0.62
Experimentation	0.33	0.33	0.79	1.00	9	9	1.00
Mathematical Analysis	0.01	0.01	0.05	1.00	2	1	0.50
Modeling & Simulation	0.31	0.30	1.17	0.96	3	3	1.00
Trade Study	0.05	0.02	0.10	0.50	3	2	0.67
Cost Analysis	0.00	0.00	0.00	—	0	0	—
System Design	0.17	0.05	0.19	0.28	4	2	0.50
Mechanical Design	0.10	0.05	0.21	0.50	2	2	1.00
Electrical Design	0.06	0.02	0.09	0.27	3	1	0.33
Software Design	0.43	0.30	0.70	0.70	9	7	0.78
Mechanical Development	0.00	0.00	0.00	—	0	0	—
Electrical Development	0.00	0.00	0.00	—	0	0	—
Software Development	1.22	1.20	1.66	0.98	13	13	1.00
System Integration & Test	0.12	0.11	0.28	0.90	6	5	0.83
Production Engineering	0.00	0.00	0.00	—	0	0	—
Quality Control	0.00	0.00	0.00	—	0	0	—
Maint & Troubleshooting	0.05	0.05	1.72	1.00	2	2	1.00
Writing & Editing	1.12	0.95	1.06	0.85	20	20	1.00
Drafting & Drawing	0.01	0.01	0.06	1.00	1	1	1.00
Searching for Information	0.17	0.14	0.29	0.82	10	8	0.80
Reading	0.68	0.43	0.67	0.64	17	13	0.76
Meetings	1.22	0.11	0.19	0.09	20	9	0.45
Briefings & Preparation	0.34	0.20	0.76	0.58	8	6	0.75
Training & Education	0.09	0.09	0.38	1.00	3	3	1.00
Project Management	0.34	0.16	0.34	0.47	8	6	0.75
Group Management	0.35	0.03	0.13	0.10	10	2	0.20
System Management	0.04	0.00	0.00	0.00	3	0	0.00
Other	0.30	0.00	0.00	0.00	3	0	0.00
TOTAL	8.83	5.31	12.65	0.60			

Table B-1. Summary data for computer tool utilization at Company 2 for 44 participating engineers during 1988.

APPENDIX C. Compiled List of Productivity Multiplication Factors Attributed to CAD/CAM.

Tool Category	Prod.Mult.	Source of Data
Drafting		
Engineering drawings (repetitive)	4	Bowman & Bowman, 1987
Simple logic drawings	4.5	Chasen, 1980
Single line drawings	3.5	Chasen, 1980
Wiring diagrams	3	Chasen, 1980
A and B Engineering drawings	2.8	Miller & Kelley, 1984
Fabrication drawing	5	Ristine, 1980
Stock drawings	4.3	Chasen, 1980
Sheet metal drawings	3.7	Chasen, 1980
Extrusion drawings	3.2	Chasen, 1980
Structural steel	1.5	Chasen, 1980
Assembly drawing	4	Ristine, 1980
Assembly drawings	3.7	Chasen, 1980
Silk Screen (single layer)	4	Ristine, 1980
Solder Mask (single layer)	4	Ristine, 1980
Mechanical diagrams	4	Briggs, 1980
Detail aircraft drawings	2.4	Chasen, 1980
Layout drawings (tool design, etc.)	1.7	Chasen, 1980
Piping layout	1.25	Chasen, 1980
Electrical & Electronic Design		
Silicon Compiler	100+	Wallich, 1984
Computer system design	3	Swerling, 1982
Schematic Generation	2	Ristine, 1980
Net List	20	Ristine, 1980
Circuit Routing	5	Ristine, 1980
Component Packaging & Placement	5	Ristine, 1980
IC Mask Design	Impossible w/o CAD	Miley, 1980
Design Verification	3	Ristine, 1980
Photoreduction & plotting	5	Ristine, 1980
Inspect Artwork	20	Ristine, 1980
Engineering Change Orders	20	Ristine, 1980
Diagram revisions	20	Ristine, 1980
Diagram revisions	10	Briggs, 1980

Tool Category	Prod.Mult.	Source of Data
Manufacturing & Process Control		
Taping & Digitizing	5	Ristine, 1980
NC Drill & Insertion tape preparation	20	Ristine, 1980
NC tape preparation	2.7	Chasen, 1980
Instrumentation diagrams	4	Briggs, 1980
Instrumentation diagrams	3	Chasen, 1980
Control diagrams	4	Briggs, 1980
Automated circuit board testing	20	Tullos, 1983
Manufacturing & Logistics Support		
Parts List	10	Ristine, 1980
Management & Communications		
Communications & documentation	2.2	Miller & Kelley, 1984
Planning	2.7	Miller & Kelley, 1984

Planning Formula for Calculation of Productivity Ratio and Cost Reduction Factors

H_1 = Manhours for any defined task, set of tasks, or project prior to the introduction of CAD/CAM.
H_2 = Manhours on the same basis as H_1 except that they are the hours unaffected by CAD/CAM. H_2 is a subset of H_1.
H_3 = Manhours spent at the console to produce the same amount of work previously done in $(H_1 - H_2)$ hours.

P.R. = Productivity Ratio = $(H_1 - H_2)/H_3$.

R_m = Average manhour rate.
R_c = Console rate.
K = Estimated saving attributable to non-direct benefits of CAD/CAM.

C.R. = Cost Reduction = $K + (H_1 - H_2)R_m - H_3R_m - H_3R_c$.

(Chasen, 1980)

APPENDIX D. A Taxonomy of Engineering Work Tasks

The following taxonomy of engineering tasks was developed during a study of two New England electronics firms employing electrical, mechanical, and software engineers. A taxonomy for other types of engineering, such as civil, aeronautical, and chemical engineering, would differ primarily in the "Synthesis" (Design and Development) tasks (see Section D.3.). This taxonomy is identical (except for paragraph markings) with on-line references provided for engineers filling out the Engineering Work Questionnaire at both firms.

D.1. ENVIRONMENTAL SCANNING.

Engineers are often called upon to perform environmental scanning functions, including the evaluation of markets, user requirements, and technologies. In combination, these three types of evaluation enable the firm to pose (and attempt to answer) the questions: "Is there a profitable market for my product? Who are my competitors? What is my competitive advantage?"

D.1.1. Market Evaluation.

Evaluation of the current economic/business environment, in an attempt to determine the competitive posture of the firm's current and future products, processes, and/or services.

Market evaluation is performed by marketing analysts, usually possessing an M.B.A. (preferably in conjunction with a technical B.S. or extensive operational experience in the market area).

D.1.2. User Requirements Evaluation.

Evaluation of user/customer functional needs or requirements, either for designing new products in the firm's product line, or for product improvement planning.

The evaluation is usually conducted by operations analysts (individuals with extensive practical experience in the user field) and/or by researchers (engineers and scientists) who have conducted in-field studies of users in an operational environment.

D.1.3. Technology Evaluation.

Evaluation of existing and near-term technologies for use in product improvement, or new products.

Technology evaluations are generally conducted by engineers and scientists, or by marketing analysts with technical backgrounds.

D.2. ANALYSIS.

Literally, a dissolution of a whole into parts. In engineering, the initial phase of engineering design, often considered the "R" (Research) of R&D. Analysis is a problem-solving activity, and includes problem identification, idea generation, experimentation, mathematical analysis, system modeling and simulation, cost estimation, and tradeoff analysis. These phases of analysis are usually interactive (and sometimes overlapping).

D.2.1. Problem Identification.

In problem identification, the engineer "scopes" the task by identifying functional requirements (based on user requirements evaluation, see 1.2), and the capabilities and limitations of available technologies and designs (based on technology evaluation, see 1.3). This task includes system interface definitions and performance requirements.

Problem identification is generally performed by marketing analysts, operational specialists, and engineers working as a team.

D.2.2. Idea Generation.

In idea generation, the engineer generates one or more ways to solve the problem, scoped and identified in 2.1. These ideas are often adaptations of previously chosen solutions to similiar problems. The innovation process is an important part of idea generation. Idea generation is usually iterative (back to the drawing board!).

Idea generation is generally performed by marketing analysts, operational specialists, and engineers working as a team.

D.2.3. Experimentation.

In experimentation, the engineer puts an idea, a technique, a product, or a process to the test in a controlled and instrumented environment. Setup of the experimental instruments and data collection (but not analysis) are considered part of the experimentation process. Several packages for computer control of laboratory instrumentation and automated data collection are currently available on the market.

Because experimentation usually requires an understanding of underlying theory, the experiments are often designed by engineers and scientists possessing a B.S. degree (or better)in a relevant field. Once the experiment has been designed, the engineer or scientist can be assisted by junior engineers and engineering technicians in the instrumentation and data collection.

D.2.4. Mathematical Analysis.

Data gathered during field studies, experiments, and simulations are analysed using various mathematical tools, which include (but are not limited to) statistical analysis, circuit analysis, spectral (Fourier) analysis, and finite element analysis (FEA). Specialized forms of mathematical analysis include modeling & simulation (see 2.5) and tradeoff analysis, sometimes referred to as trade studies (see 2.6).

Calculations for mathematical analysis are usually performed (at least initially) using paper, pencil, and hand calculator. Computer tools are often employed in later phases of analysis, usually when the solution of simultaneous equations are necessary, or when simulations are in order, as in modeling & simulation. Software packages, which run on various PC's and mainframes, are available for mathematical analysis. These packages range from flexible, general-purpose spreadsheets to highly specialized scientific/engineering math packages such as signal processing, statistical analysis, nonlinear equation-solving, and linear programming.

Because mathematical analysis usually requires an extensive understanding of underlying theory, this work is generally performed by formally trained engineers and scientists.

D.2.5. System Modeling & Simulation.

Actually a specialized subset of mathematical analysis. Data, following mathematical analysis, is used to form a mathematical model of the product or process being analyzed. This model, with appropriate boundary conditions, is then subject to one or more forms of mathematical analysis, such as linear programming or simulation. Many computer software packages are available for system modeling and simulation (linear and nonlinear, discrete and continuous). Some simulation software (such as FEA or electronic circuit performance simulation) is usually included as an integral part of Computer Aided Design (CAD) systems.

D.2.6. Tradeoff Analysis (Trade Study).

A form of mathematical analysis, in which the technical and cost performance of various alternatives are compared and contrasted, resulting in the selection of an "optimal" solution given the weighting criteria. Software used for tradeoff analysis, sometimes called a "trade study", include spreadsheets and linear programming packages.

This form of analysis is generally performed by marketing analysts, systems engineers, and project managers working as a team.

D.2.7. Cost Estimation and Bidding.

Engineers and engineering managers from both Design and Manufacturing functional areas are often called upon to compile pricing information for various alternative solutions to the design problem. This information is used as an input to Tradeoff Analysis (2.6) to assist in the selection of an optimal design, and in the preparation of a Bid (estimated price) of a proposed product, process, or service.

D.3. SYNTHESIS.

Literally, an integration of parts into a whole. In engineering, the phase following the preliminary, analytic portion of the problem solving process, often associated with the "D" (Development) of the R&D process. Synthesis includes preliminary (system-level) and detailed subsystem design of prototype and production products, processes, or services. Engineers document their designs through engineering specifications and drawings; and the development, test, and debugging of pre-production prototypes.

Design is interactive with other engineering tasks, including: user requirements and technology evaluation, problem identification, system modeling and simulation, and tradeoff analysis. Preliminary design is most often performed in the proposal stages of contractual and internal research and development (IR&D) projects. Detailed design and development are most often performed under contract or during an IR&D project.

Preliminary design (sometime known as system design) is usually performed by engineers with extensive technical experience (usually five years or more) and familiarity with user requirements. This phase is highly iterative, defining the technical approach to problem solving in the light of functional requirements, costs, risk, etc. Once subsystem requirements have been defined in the preliminary system specification, detailed design can begin. Detailed design of components (such as a electrical design of a VLSI chip, or production of a software module) often requires an understanding of basic engineering, mathematical, and scientific theory, and is generally performed by engineers possessing at least a B.S. in a relevant engineering, science, or math field. Development is performed by engineers, technicians and programmers.

D.3.1. System Design and Specification.

System engineering design includes the design of top-level hardware and software systems architecture, and is generally performed by teams of marketing analysts, operational specialists, systems engineers, hardware engineers, software engineers, and production engineers working as a team. System specification includes overall system functional (performance) requirements and external/internal interface definition. Systems specifications are generally documented as "A-Level" Specifications.

D.3.2. Mechanical Design and Specification.

Mechanical engineering design includes (but is not limited to) structural, power and thermal design and associated drawings, and is generally performed by mechanical engineers. Mechanical engineering specifications are usually part of A-, B- and C- Level Specifications. CAD packages are widely available to automate the mechanical design process, and generally include solid modeling and FEA capabilities, integrated with automated drawing generators.

D.3.3. Electrical Design and Specification.

Electrical engineering design includes (but is not limited to) analog and digital circuit design, signal processing, data and voice communications, and electrical power distribution. Electrical engineering specifications are usually part of A-, B- and C-Level Specifications. CAD packages are widely available to support both digital and analog circuit design, circuit simulation, board layout, and drawing generation.

D.3.4. Software Design and Specification.

Software design includes software architecture design, interface specification for software modules, algorithm development, flowcharting, and the writing of pseudocode. Software specification includes software requirements definition and software interface definition, most often a part of B- and C-Level Specifications. Software packages for flowcharting and software requirements tracking are widely available for mainframes, minis, and personal computers.

D.3.5. Mechanical Development and Prototyping.

Mechanical development includes refinement of mechanical engineering designs and drawings to make them production-ready. Mechanical prototyping includes the production of sub-scale and full-scale models and pre-production structural prototypes. (Testing of prototype performance, to include data collection, falls under Experimentation, 2.3.)

D.3.6. Electrical Development and Prototyping.

Electrical development includes refinement of electrical and electronic designs and drawings to make them production-ready. Electrical prototyping includes the production of prototype electronic components (such as wire-wrapped boards, or pre-production batches of VLSI chips), and the electrical interconnection of pre-production components into a functioning whole. (Testing of prototype performance, to include data collection, falls under Experimentation, 2.3.)

D.3.7. Software Development and Prototyping.

Software development includes writing and debugging software (known as "lines of code"). Numerous software development packages (which include editors, compiliers, cross-compilers, linkers, debuggers, and software libraries) are available for a wide number of languages and host computers.

Software prototyping includes the development, fielding, installation, evaluation, and debugging of pre-production software, either as a stand-alone product (Alpha and Beta testing), or as a part of a larger system testbed (hardware and/or software) to provide testable prototype functionality.

Software development, prototyping and Alpha (in-house) testing are done by computer scientists, software engineers, and programmers. Beta testing of pre-release software is performed by specially selected lead users.

D.3.8. System Integration, Testing, and Debugging.

System integration includes the combination of hardware and software components (both prototype and production) into a functioning whole. System test and debugging includes the test procedures which verify that hardware and software components are functioning together as designed, and to make engineering changes as required to ensure the performance of the system. (This testing does NOT include any testing of the overall system to determine the limits of the system's performance; such testing falls under Experimentation, 2.3.)

System integration, testing, and debugging are performed by operational specialists, engineers, technicians, and programmers.

D.4. PRODUCTION AND MAINTENANCE.

Production and maintenance activities fall include manufacturing and production engineering, quality assurance (sometimes called quality control), troubleshooting, and maintenance.

D.4.1. Manufacturing and Production Engineering.

Manufacturing and production engineering includes manufacturing process development and process/production control. A number of computer aided manufacturing (CAM) systems exist to automate the process/production control function.

Manufacturing and production engineering is performed by engineers, preferably with an industrial engineering background.

D.4.2. Quality Assurance Engineering.

Quality assurance engineering includes the testing of some or all of a production batch, to assure that the product meets internal, customer, or federal specifications or standards.

Inspection of batch samples is generally performed by technicians. Statistical analysis of batch samples is usually done by engineers with academic backgrounds in industrial engineering and/or statistical analysis.

D.4.3. Troubleshooting & Maintenance.

Troubleshooting and maintenance activities includes prognostic, diagnostic, and repair work performed on production (hardware and/or software) systems, either at the production site or at field sites. These tasks also include the installation of product improvements (such as new software, or a faster modem) at field sites.

Troubleshooting and maintenance activities are generally performed by engineers, technicians, and programmers.

D.5. COMMUNICATION.

Engineering work is complex, requiring cooperation between several engineers with different skill specializations. This cooperation between engineers, together with the management of these engineers by functional and program managers, depends on various forms of communication. Some of this communication is highly informal in nature, taking place as an integral part of a work task, such as mathematical analysis. For instance, an engineer may ask another one about setting up a statistics problem on the PC.

Other forms of communication can be considered as tasks in their own right. These communication tasks are verbal, written, and graphic in nature, and include: discussions, meetings, writing, drawing, reading, searching for information, and preparing seminars, demonstrations, and briefings. Also included under communications tasks are education and training activities.

D.5.1. Discussions and Meetings.

Discussions and meetings are gatherings of two or more people, in which the primary activity is communication. The gathering may be formal (e.g. Roberts Rules of Order), informal, or casual in nature. Technical or management matters are usually discussed, although social communications may take up a significant fraction of the overall time spent in a discussion or meeting.

D.5.2. Writing and Editing.

Writing is a task involving the generation of text (internal memoranda, specifications, journal articles), as a means of recording and/or communicating information. The text can stored and transmitted electronically and/or physically.

Editing is a task involving the alteration of text for a specific purpose, usually as a means of correcting some deficiency in the text product (e.g., correcting an incorrectly spelled word, restructuring a poorly constructed sentence, or altering an incorrect value in a table.)

D.5.3. Drafting and Drawing.

Drawing is a task involving the generation of visual (or graphic) material (sketches, illustrations, figures), as a means of recording and/or communicating information. The graphics can stored and transmitted electronically and/or physically.

Drafting is a formalized type of drawing task, intended for the generation of engineering drawings and blueprints. Such drawings, because of the special methodologies and tools required for their production, are generally produced by draftsmen (technicians) and engineers trained in drafting.

D.5.4. Searching for Information.

This is a task in which the engineer searches for information to support problem solving. The information can be written (text, graphics), electronic, or verbal, and can involve library and other hard-copy archival searches, electronic information retrieval, and face-to-face or telephonic inquiries. Searching for information does not include experimental data collection.

D.5.5. Reading.

The reading task includes the scanning (and reading for content) of written materials as an input method for the problem solving process. Written materials include, but are not limited to, professional and trade journals, technical books and magazines, internal company memos, electronic mail, and product specifications.

D.5.6. Presentations, Demonstrations, and Briefings.

This task includes the preparation and presentation of lectures, seminars, demonstrations, and briefings. It does not include attendance at one of these functions (they fall under meetings or education/training), or the preparation of graphics such as vugraphs, charts (which falls under drawing).

D.5.7. Education and Training.

Education and training includes any activity, formal or informal, intended to teach the engineer new skills (such as how to use new lab instrumentation or data base software). It includes attendance at, and teaching of, classes and instructional seminars.

D.6. MANAGEMENT ACTIVITIES.

Engineers are often called upon to manage either technical projects, or other engineers. In most companies, engineers follow a "dual ladder" career path; at some mid-career point, the engineer can choose to follow either technical or management specialization. Often, group and project management is one career aspect which differentiates the degree-holding engineer from his technician cohorts.

D.6.1. Project and Proposal Management.

Project management is a tactical (business area or divisional scope) activity for the control of one project or product line at any point during its life cycle. Project management is a communications-intensive task, usually stressing day-by-day management of project operations. Some advanced planning is done for product improvement/replacement in order to keep the product line competitive in a changing marketplace and user environment. The project can either be contractual work for a customer, or internally contracted work such as internal R&D.

Proposal management is a type of project management, concentrating on the earliest phases of the product's life cycle, including conceptual studies, preliminary design, and bid & proposal work.

Project and proposal management are generally performed by engineering managers, usually with a combination of technical and business degrees.

D.6.2. Unit, Group and Section Management (Functional Management).

Unit, group, and section management are tactical (business area or divisional level) management activities, intended for the control of functional engineering activities below the division level (engineering managers below divisional chief engineer). Unit managers may have as few as three engineers and technicians working for them; section managers may have several hundred.

D.6.3. Strategic Planning & Executive Management.

Strategic planning activities encompass division- and corporate-level planning, such as the development of a 5-year market capture strategy, or divisional/corporate investment planning (to include R&D).

Executive management includes functional and business-area decision making activities which impact divisional and corporate level technical or business operations.