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Computer Aided Engineering and Project Performance: Managing a Double-Edged Sword

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Abstract

Computer aided engineering tools are like a double-edged sword. Properly employed, CAE tools improve engineering productivity, and help keep technical projects on schedule and under budget. For some kinds of work, CAE tools can also stimulate creativity.

However, computer tools can have equally detrimental effects. For less structured engineering tasks, such as preliminary analysis and problem solving, the use of inappropriate or inadequate tools can severely constrain performance. By encouraging the "cloning" of old solutions, computer tools can also stifle creativity and yield sub-optimal designs through negative biasing.

This paper presents the results of field research conducted at two U.S. electronics firms, and recommends a strategy for employing CAE tools which maximizes the benefits of CAE while avoiding or minimizing the pitfalls. A triangulation technique consisting of participant observation, interviews, and questionnaires was used to collect data from 116 engineers and 32 project managers over a two year period.

The "average" engineer's work day spans many different kinds of technical and non-technical tasks, including A certain amount of managerial work. The engineers in the present sample, on average, spend about 45 percent of the day performing technical tasks traditionally associated with engineering. Because engineering is a group-oriented activity, about 40 percent of the average day is devoted to communicating in some fashion.

Engineers in our work sample also use a wide range of computer tools in their work, ranging from simple editors and drawing tools, to sophisticated workstations and integrated application toolkits. Most of today's CAE tools are specialized "single-function" tools aimed at leveraging personal productivity. Engineers with access to more sophisticated tools in their immediate work are more likely to use these tools in their work ($r = +0.52$). Furthermore, projects whose engineers make greater use of computer tools are more likely to be under budget ($r = +0.33$).

Given their capabilities and limitations, today's CAE tools do not always leverage engineering productivity. Use of computer tools for less structured work performed early in the work cycle is correlated ($r = -0.30$) with less innovative projects. By contrast, use of computer tools for highly structured work performed late in the work cycle is positively correlated ($r = +0.35$) with more innovative projects.

INTRODUCTION

Our research goal, simply stated, is to better understand what computer tools engineers use for different kinds of work and how this use relates to the engineers' performance. What kinds of tasks do engineers perform? What sort of computer tools do engineers use for these tasks? To what extent are they used? And how is the use of computer tools by engineers related to technical performance at the level of the project?

The Nature of Engineering Work.

A number of studies (Ritti, 1971; Allen, Lee & Tushman 1980; Marples, 1961; Allen, 1966; Frischmuth & Allen, 1969) have examined the nature of engineering work, and have found it to comprise many types of activity. 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). But engineering work is not entirely devoted to technical problem-solving. Engineers engage in many other activities, such as technical communication, management, and administrative work. Some studies would indicate that engineers spend as little as 20 percent of their time on technology related tasks (Miller & Kelley, 1984).

Engineering tasks are thus diverse, ranging from technical design, development, and test (traditionally associated with engineering work) to management, manufacturing, communications, and market analysis. Based on a preliminary study (Murotake, 1990) we have grouped these tasks into eight categories (Table I): environmental scanning, analysis, design,

Table I

The Nature of Engineering Work

Environmental Scanning
- Market Evaluation
- User Requirements Evaluation
- Technology Evaluation

Design (Synthesis)
- System Design & Specification
- Mechanical Design & Specification
- Electrical & Electronic Design & Specification
- Software Design & Specification
- Mechanical Development & Prototyping
- Electrical & Electronic Development & Prototyping
- System Integration, Testing & Debugging

Production And Maintenance
- Manufacturing & Production Engineering
- Quality Assurance Engineering
- Maintenance & Troubleshooting

Communication
- Discussions & Meetings
- Writing & Editing
- Searching For Information
- Reading
- Presentations, Demonstrations & Briefings
- Education & Training

Drafting and Drawing
- Briefing Preparation/Presentation
- Information Search Education and Training
- Reading
- Other: Administrative activities, holiday and vacation, travel, etc.

Production And Maintenance
- Manufacturing & Production Engineering
- Quality Assurance Engineering
- Maintenance & Troubleshooting
- Communication
- Discussions & Meetings
- Writing & Editing
- Searching For Information
- Reading
- Presentations, Demonstrations & Briefings
- Education & Training

Management Activities
- Project & Proposal Management
- Unit, Group & Section Management
- Strategic Planning & Executive Management

Software Design
- Software Coding & Debugging
- Overall System Design
- Overall System Integration
- Production Management\
- Production & Process Engineering
- Administrative /Group Management Quality Control

Technical Management
- Planning
- Technical Communication
- Other Communication
- Writing and Editing
- Meetings/Seminars (attendance)

development, production, management, communication, and other.

Computer Tools for Engineers.

Computer tools are available to address most major components of engineering work, including mathematical analysis, engineering design and development, desktop publishing, and technical communication. The integration of diverse tools in a workstation tool kit is one of the major contributions 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)

Engineers at the two research sites spend, on average, several hours per day performing a wide range of engineering work (Figure 1). 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.

Making Engineers More Productive with Computer Tools

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 (GE/CR&D 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 two-thirds 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

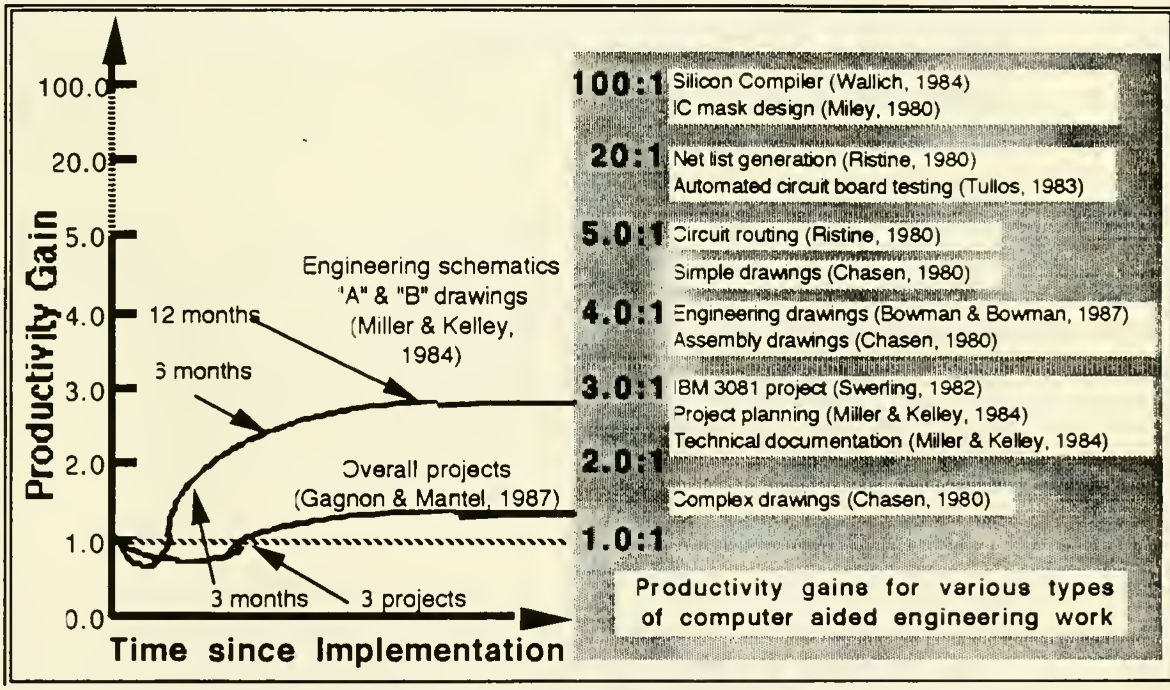

Figure 1 Productivity gains reported in different CAE implementation studies. The lower portion of the figure shows how productivity gains change with time. Note the initial "learning curve" dip in productivity, followed by productivity gains. In general, productivity gains increase with increasing task complexity and repetitiveness (Murotake, 1990).

(Wallich,1983), 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). 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 two-thirds 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,1983), 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 1). In one case study of PC-based CAE at a cathode ray tube manufacturer, 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 three 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, 1980).

The Dilemma - Balancing Productivity and Innovativeness.

There is a "dark side" to computer tools. Productivity and innovativeness compete for the same resources, and can be at odds. In an 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 is 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 suboptimal designs that happen to be on the solution menu (Naisbitt, 1983). 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 and innovativeness can suffer (Wallich, 1984 ; Murotake, 1990).

HYPOTHESES

1. Given equal accessibility, the more sophisticated the computer tool the more it will be used by engineers.

2. The greater the use of computer tools by a project team, the greater the performance of the project, as measured against its planned schedule and budget.

3. The greater the use of computer tools by a project team, the greater the performance of the project, as measured by ratings of technical quality and innovativeness of engineering work.

RESEARCH METHOD

The research program used a fully replicated experimental design at two U.S. electronic firms. 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 from the two firms. Measurements were made of the type of engineering work performed, the degree to which computers were used, and project performance. This was done by administering questionnaires to a sample of 116 engineers and their project leaders on 32 projects. Empirical data on approximately 3500 man-hours of engineering work were collected.

Company 1 is a defense electronics division of a large technology-based conglomerate. Its fourteen hundred employees design and manufacture electronic products for the U.S. defense market. Company 1 engineers have shared access to personal computers and video terminals in their work bays, linked to networked minicomputers; limited numbers of CAD engineering workstations are available in special CAD areas.

By contrast, Company 2 is the R&D division of a commercial computer company About the same size as Company 1, Company 2 is a CAD/CAM pioneer with major market share in the world-wide computer workstation market, and has aggressively pursued the goal of a paperless office and lab environment for its engineers. It has created a Computer Aided Engineering (CAE) environment that is a model for the industry. Engineers, managers, and secretaries all have powerful workstations on their desks. The workstations are networked with high-capacity file servers, print servers, and other computers. High-bandwidth Local Area Networks (LANs) bridge networks between buildings, while high-speed telephone data lines link Company 2's network with other networks across the globe.

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, project management tools, 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; these can be used to aid tin 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 in addition to a full suite of office automation tools. Hardware is generally a network of advanced personal computers or workstations with access to mainframes or distributed processing.

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 (Table II).

Table II

Sophistication of the Computer Tools Available to the Engineers (32 Projects)

	Company 1		Company 2	
Sophistication of Available Tools	Projects	Percentage of Projects	Projects	Percentage of Projects
No Tools Available	0	0%	0	0%
Basic Office Automation	3	14	0	0
Limited Technical Capability	12	57	5	45
Advanced Technical Capability	6	29	6	55
Total	21	100%	11	100%

Engineers use computers much more at Company 2 than at Company 1 (Figure 2). Given Company 2's "one engineer, one workstation" credo and their rich tools environment, this comes as no surprise.

There is a substantial correlation ($r = 0.52$) is between the use of computer tools, and the sophistication of available tools. Controlling for this factor yields dramatic results ($F = 8.72$; $p < 0.01$) (Murotake, 1990), overshadowing the statistical significance of other factors, such as company (Figure 3).

In all activities, with the exception of development, there are significant positive correlations between computer use and the sophistication of available tools in the work area (Table III). That is, the more sophisticated the tools available to the engineers, the more time engineers spend using these tools for engineering analysis, design, and communication related tasks.

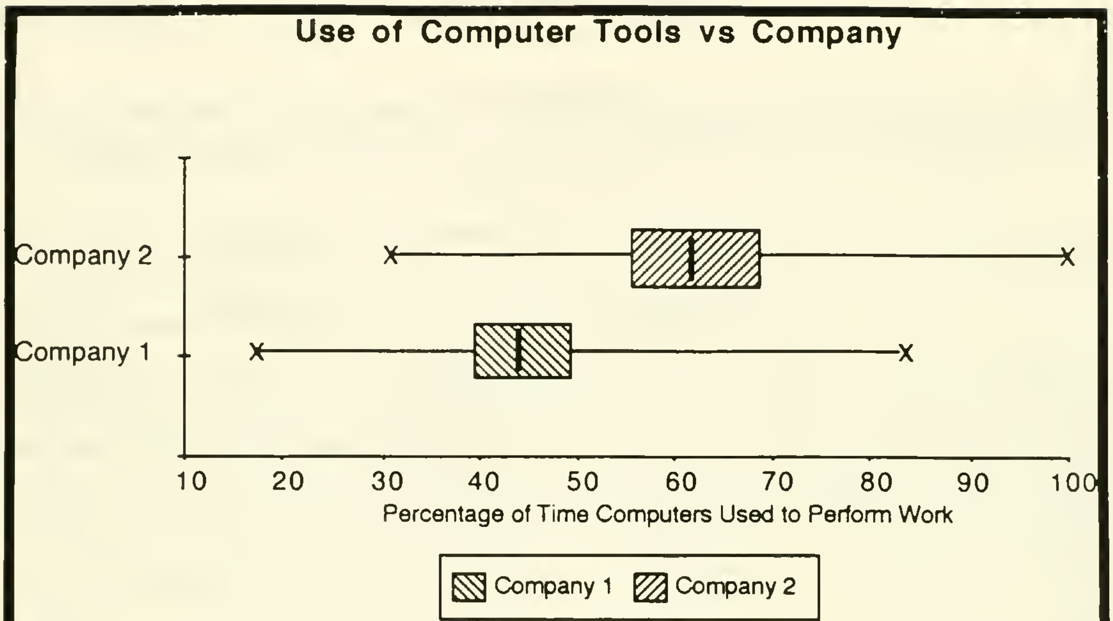

Figure 2 Box-and-whisker plot of the percentage of time computers are used to support engineering work at Company 1 (n=21, mean=44.52%, SD=4.78%) and at Company 2 (n=11, mean=61.09%, SD=6.61%). Although engineers at both companies make extensive use of computer tools, Company 2 engineers use computers substantially more than their Company 1 counterparts. 1988 data.

Computers and Project Performance.

Projects whose engineers make greater use of computer tools are slightly more likely to be on or under the planned budget ($r = -0.33$, $p < 0.05$). This supports the hypothesis that use of computer tools is correlated with higher project performance as measured by being on or under budget.

The partial correlations of computer use with quality and innovativeness of the work provide some interesting observations (Table IV). In performing the partials we control for the sophistication of available tools, since this varied considerably across groups. We also control for other extraneous variables, such as the level of required technical sophistication in the work, project phase and project schedule, which are substantially correlated with technical performance (Murotake, 1990). None of the correlations are statistically

Table III

Computer Use as a Function of Sophistication of Available Tools

Nature of Work	Correlation (r)
Idea Formulation	0.40
Design	0.60
Development	0
Communication	0.40
Overall	0.52

Table IV

Relationship Between Computer Use and Evaluated Quality and Innovativeness of Project Results

Correlation of Computer Use With: Quality of Work	Correlation of Computer Use With: Innovativeness	Controlling For:
0.18	-0.06	None
0.14	-0.14	Sophistication of Available Tools
	-0.04	Required Technical Sophistication
	-0.03	Project Phase
0.17		Project Staffing
0.13		Project Schedule
0.12	-0.14	All

significant.

Examining the data in different phases of the engineering design and development process reveals some very interesting results. The overall lack of correlation between computer use and project performance results from two opposing relations which nullify each other. At the beginning of the engineering process (idea formulation), increased use of computers is negatively correlated with innovativeness ($r = -0.30$), significant at the $p < 0.10$[1] 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 $p < 0.05$[2] level (Figure 4). And, while use of computer tools in the documentation and communication area is slightly correlated with higher quality ($r = 0.22$), it is (not surprisingly) also correlated with less innovative work ($r = -0.21$).

Why the dramatic difference in the correlation coefficients as one moves through the engineering process from idea formulation, through design, to engineering development? We believe there are two basic mechanisms at work. The first is related to the degree of structure inherent in the work, and the "breadth" (or bandwidth) of the work. The second is related to the "cloning" of solutions using computer tools.

Computer Tools and Work Structure. As tasks become more highly structured, computer tools become more capable of leveraging engineering productivity (Figure 3). Most computer tools used by engineers today have sharply focused functionality. Each tool - by design - is matched to one or two kinds of work (word processors are

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[1]A two-tailed test is used, since this direction of relationship was not hypothesized.

[2]One-tailed.

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 and layout using CAD) usually support only one structured method, technique, or algorithm. When "matched" to their intended role, computer tools can leverage an engineer's productivity. When "forced" to perform work outside their intended function, computer tools may hamper the engineer's efficiency. Also, while creative adaptation of a computer tool for a new application may itself be innovative, forcing a tool to do work for which it is not intended, or requiring engineers to use inadequate computer tools, can also have adverse impacts on project technical performance (Murotake, 1990).

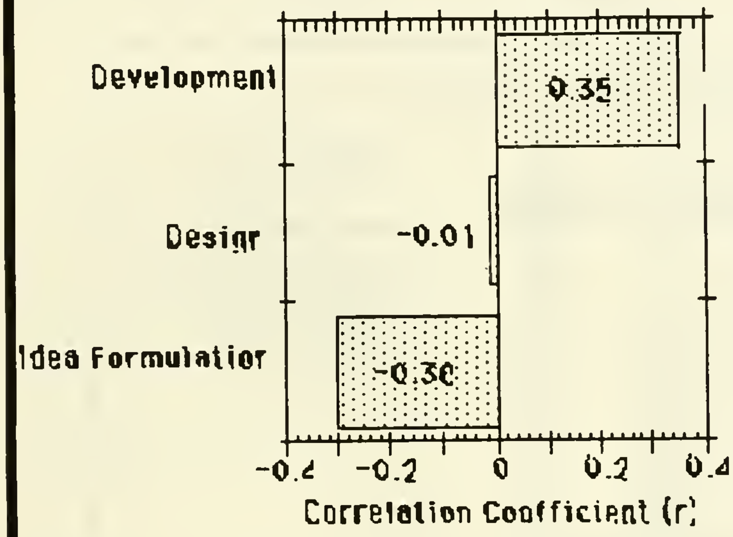

Figure 3 For highly structured tasks, like engineering development work, use of computers is significantly correlated with more innovative work. For loosely structured tasks, such as preliminary analysis and problem definition, use of computers is significantly correlated with less innovative work.

Problem definition and problem solving (analysis) work, often performed early in the engineering cycle, is relatively unstructured and multi-disciplinary in nature. This kind of work often calls for more innovativeness than any other kind of engineering work. The lack of structure, and multi-disciplinary nature precludes any one computer tool from supporting the analysis task, while the need for creativity defies the use of "existing solutions" for optimal solution. By contrast, engineering development is highly structured ("cookbook", "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 engineering development is the computer tool's forte, an expectation well supported by fact (Murotake, 1990). CAD and CAE

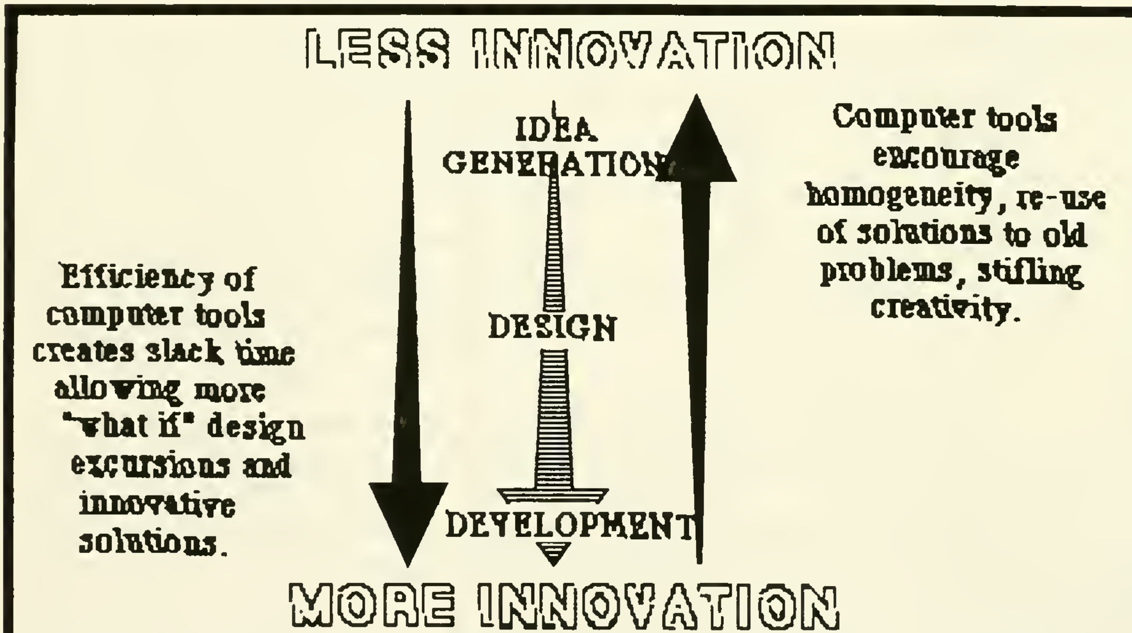

Figure 4 The efficiency gained by the use of computer tools creates slack time which, in turn, can be used to support innovative activity. On the other hand, the tendency to "crank out" homogenous solutions stifles creativity, balancing the efficiency benefits of computer tools. Both can currently be achieved only for structured tasks like engineering development, for which computer tools are well suited.

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. The desire to "clone" previous solutions to problems is high when using computer tools, since the reuse of previous solutions is a key part of the computer's ability to improve productivity (Naisbitt, 1983). The time and effort needed to set up a new solution for each problem threatens higher productivity. However, reuse of old solutions can lead to homogeneity in problem-solving approaches which, by definition, stifles the development of innovative solutions (Figure 6). Further, old solutions may represent a "negative biasing set", resulting in suboptimal solutions to the problem at hand (Allen & Marquis, 1963).

SUMMARY AND CONCLUSIONS.

While use of computer tools for preliminary analysis and problem solving is correlated with lower innovativeness ($r = -0.30$, $N = 32$, $p < 0.10$)[3], the use of computer tools for engineering development work is significantly correlated with more innovativeness ($r = -0.35$, $N = 32$, $p < 0.05$). Thus, of computer tools lead to ***less* innovative work** when used to support engineering **analysis and problem solving** but ***more* innovative work** when used to support **engineering development**.

The reasons are twofold and very simple. Computer tools make engineers very efficient for certain types of tasks, allowing time to be spent in innovative pursuits. However much of the efficiency is achieved by ‘cloning’ old solutions, encouraging homogeneity, stifling creativity and biasing engineers toward convenient but suboptimal solutions. In addition, computer tend to be narrowly 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 research:

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[3] Two-tailed test of significance.

1. **Create and manage slack.** Computer tools can be used to leverage individual and group productivity, create in slack in manpower. This slack should be managed in a way which will produce both innovation-stimulating tasks for engineers and increased productivity for the firm.

2. **Use appropriate tools.** Since the nature of engineering work varies considerably, engineers should be provided with a complete and versatile 'toolkit' of computer hardware and software tools. Current software technology best supports structured, repetitive tasks with substantial amounts of data or numerical manipulation. Use of computer tools with a narrow functional focus to support less focused work, or work with high 'cognitive bandwidth', can result in lower performance. Software capabilities are broadening with time, but for the present, caution is advised.

REFERENCES

Abernathy, W,J, (1978). **The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry.** Baltimore: Johns Hopkins University Press.

Allen, T.J. (1966). Studies of the problem-solving process in engineering design, **IEEE Transactions on Engineering Management**, **13**(2), 72-83.

Allen, T.J., D.M.S. Lee and M.L. Tushman (1980). R&D performance as a function of internal communication, project management and the nature of work, **IEEE Transactions on Engineering Management**, **27**(1), 2-12.

Allen, T.J. and D.G. Marquis (1963). Positive and negative biasing sets: The effect of previous experience on research performance, **IEEE Transactions on Engineering Management**, **11**(4), 158-162.

Frischmuth, D.S. and T.J. Allen (1969). Amodel for the description and evaluation of technical problem-solving, **IEEE Transactions on Engineering Management**, **16**(1), 58-64.

Gagnon, R.J. and S.J. Mantel, Jr. (1987). Strategies and performance improvement for computed-assisted design, **IEEE Transactions on Engineering Management**, **34**(4).

General Electric/Corporate Research and Development/Automation and Control Laboratory, C.S. Draper Laboratory and the MIT Center for Policy Alternatives (1976). **Product Systems Productivity Research: A Collaborative Study**, National Science Foundation.

Gold, B. (1982). Robotics, programmable automation, and international competitiveness. **IEEE Transactions on Engineering Management 29**(4), 135-145.

Johnson, L. (1984). Successful application of high tech in technical design and production. **IEEE Engineering Management Review 12**(1), 14-18.

McDermott, K. (1984). The utilization of the microcomputer word processor in engineering management. **IEEE Engineering Management Review 12**(1), 45-48.

Machover, C. & R.E. Blauth (1980). **The CAD/CAM Handbook.** Bedford MA: Computervision.

Marples, D.L. (1961). The decisions of engineering design, **IRE Transactions on Engineering Management, 8**(2), 55-71.

Miley, D. (1980). Integrated circuit design. Chapter 5.2 in Machover & Blauth (Eds.), **The CAD/CAM Handbook**. Bedford MA: Computervision.

Miller, J. & W. Kelley (1984). Personal computers, an engineering productivity tool. **RCA Engineer** (May/June).

Murotake, D.K. (1990). **A Double-edged Sword: Relationships Between the Engineering Use of Computer tools and Project Performance.** Doctoral dissertation, Massachusetts Institute of Technology, Sloan School of Management.

Naisbitt, J. (1983). The outlook: Computer trends. **IEEE Spectrum 20**(11), 110-119.

Nelson, R. & S. Winter (1977). In search of a useful theory of innovation. **Research Policy 6**, 36-76.

Ritti, R. (1971). **The Engineer in the Industrial Corporation**, New York: Columbia University Press.

Swerling, S. (1982). Computer-aided engineering. **IEEE Spectrum 19**(11), 37-41.

Tullos, R. (1983). Automated board testing: coping with complex circuits. **IEEE Spectrum 20**(7), 38-44.

Wallich, P. (1983). Automation: Design/manufacturing, **IEEE Spectrum, 20**(!), 55-58.

Wallich, P. (1984). On the horizon: Fast chips quickly. **IEEE**

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