NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 161

COMPUTER-AIDED DESIGN AND DRAFTING SYSTEMS

TRANSPORTATION RESEARCH BOARD
National Research Council

TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE 1990

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **161**

COMPUTER-AIDED DESIGN AND DRAFTING SYSTEMS

GEORGE KORTE
Reston, Va.

Topic Panel

KEITH BUSHNELL, *Lansing, Michigan*
BRUCE COSABOOM, *New Jersey Department of Transportation*
IAN M. FRIEDLAND, *Transportation Research Board*
RICHARD B. GEIGER, *Bureau of Indian Affairs*
GEORGE W. RING, *Transportation Research Board*
ARTHUR WAGNER, *Pennsylvania Department of Transportation*

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. AUGUST 1990

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTE: **The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.**

NCHRP SYNTHESIS 161

Project 20-5 FY 1987 (Topic 19-01)
ISSN 0547-5570
ISBN 0-309-04906-7
Library of Congress Catalog Card No. 90-70619

Price $7.00

Subject Areas
Planning
Facilities Design
Structures Design and Performance
Operations and Traffic Control

Mode
Highway Transportation

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Transportation Research Board evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to administrators, designers, computer personnel, and others interested in the operation and management of computer-aided design and drafting (CADD) systems. Information is provided on selection and implementation of CADD systems, current uses in state DOTs, and issues involved in managing a CADD system and CADD operators.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Most state departments of transportation either have or plan to acquire CADD systems to improve their design, drafting, and mapping operations. This report of the Transportation Research Board describes the processes for selecting and implementing a CADD system, current practices of state DOTs in applying and using CADD, and training and performance issues with respect to CADD personnel.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Robert E. Skinner, Jr., Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Herbert A. Pennock and Martin T. Pietrucha, Special Projects Engineers. This synthesis was edited by Judith Klein.

Special appreciation is expressed to George Korte, Management Consultant, Reston, Virginia, who was responsible for the collection of the data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Keith Bushnell, Retired; Bruce Cosaboom, Supervising Engineer II, CADD, New Jersey Department of Transportation; Richard B. Geiger, Deputy Chief, Division of Transportation, Bureau of Indian Affairs; and Arthur Wagner, Bureau of Design, Pennsylvania Department of Transportation.

Ian M. Friedland, Senior Program Officer, and George W. Ring, Engineer of Design, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

COMPUTER-AIDED DESIGN AND DRAFTING SYSTEMS

SUMMARY

This report was prepared using two primary research techniques. First, a literature search was conducted to gather reports, surveys, and other documents pertaining to the topic. These were reviewed and evaluated for pertinent information. A survey was sent to 55 state and provincial DOTs in the United States and Canada as well as five engineering consulting firms in the United States known to have significant experience with computer-aided design and drafting (CADD) for highway design. Completed questionnaires were returned by 45 organizations. These responses were tabulated and summarized in a computer data base. The results were then analyzed and included in this report.

The report has two primary objectives. The first is to aid state and local DOTs that are implementing CADD systems for the first time. Computer-aided design and drafting is a radically different technology than that of the traditional manual drafting and design processes. Much time, energy, and money can be wasted during the initial phases of a CADD operation while an organization learns how to put it to its best use. It has been found, however, that much of this waste can be eliminated when clear direction and sound guidance is received from more experienced CADD users.

The second primary objective of this report is to provide both new and experienced CADD users in state and local DOTs with information regarding CADD applications and personnel management policies in state DOTs.

In recent years, computer technology in general and CADD technology in particular have advanced very rapidly. These advancements have occurred in both hardware and software products and capabilities. Vendors and suppliers in the computer-graphics industry are continually making new-product announcements. For this reason, this synthesis has focused on management and application issues as opposed to state of the art in hardware and software technology. Any information focusing on hardware and software technology would be outdated almost as quickly as it was committed to paper. Such information is best obtained by subscribing to industry newsletters and periodicals and by attending association and users' group conferences that pertain to CADD technology.

Chapter 1 presents an introduction to CADD systems. It includes a brief discussion of the history of CADD technology and a description of the basic components of a CADD system including: (a) the central processing unit, (b) input devices, (c) output devices, (d) data-storage devices, and (e) software.

Chapter 2 discusses the process of selecting and implementing CADD systems. It covers the following topics: (a) management support, (b) requirements analysis, (c) vendor selection, (d) system procurement costs, (e) system implementation, (f) system operating costs, and (g) pitfalls in system selection and implementation.

Management support is a critical factor in the success of a CADD operation. This new technology is often promoted by an individual or a team who acts as a "champion" for its use. Because this champion often comes from middle management or a technical area, he or she lacks the authority to make all the changes necessary to adopt CADD technology. Therefore, the support and endorsement of an organization's top manage-

ment is needed to overcome the organizational inertia and political resistance to CADD.

A requirements analysis is the recommended first step toward the implementation of a CADD system. This process involves an assessment of: (a) current processes, (b) current costs, (c) potential CADD applications, (d) expected costs, (e) potential benefits, and (f) payback on the investment.

Vendor selection is usually the next step in the process of implementing a CADD system. Half of the DOTs surveyed indicated that they select a vendor based only on technical qualifications, whereas the rest indicated that they also considered the vendor's bid. Approximately half said that they required that the vendors conduct benchmark tests of system capabilities before making a selection.

With regard to system costs, the survey found that the average cost per graphics terminal among the DOTs surveyed fell from an average of $144,600 in 1982 to $76,200 in 1988, indicating an average decrease of 10 percent per year over this period. The synthesis also notes that with the advent of CADD software operating on personal computers (commonly referred to as PC CADD), the cost per graphics terminal has dropped even further, although the current capabilities of PC CADD systems are limited relative to minicomputer-based graphics terminals. The new PC CADD systems with new chips may soon displace graphics workstations.

With regard to system implementation, this synthesis emphasizes the need to develop a sound implementation plan and stick to it. Such a plan would include a clear definition of the following: (a) goals, (b) schedule, (c) milestones, and (d) required changes.

The synthesis discusses the costs of operating the system. These include the depreciation of the purchase cost, hardware and software maintenance charges, utilities, supplies, and the cost of ongoing user support and training. The synthesis presents an analysis of a typical system's operating costs and determines that they will amount to approximately $19 per hour (excluding operator's wages) for a two-shift-per-day operation and $38 per hour for a one-shift-per-day operation. The report then discusses the following pitfalls commonly encountered during the process of systems selection and implementation: (a) failure to obtain top management support and understanding of the CADD program, (b) failure to plan, (c) failure to anticipate all costs, (d) failure to set reasonable expectations, and (e) failure to provide a capable systems support staff.

Chapter 3 discusses current practices in the uses of CADD in state DOTs. It begins with a general description of the five major types of CADD applications, including: (a) roadway design and drafting, (b) bridge design and drafting, (c) interactive photogrammetry, (d) automated survey data collection, and (e) mapping.

The synthesis next discusses the systems that are currently in use at state DOTs. Table 1 presents the answers to all survey questions regarding hardware currently installed at state DOTs.

Software use is then discussed. The survey identified 14 engineering design functions accomplished by state DOTs using CADD. They are:

- roadway drafting,
- bridge drafting,
- generating cross sections,
- traffic analysis,
- architectural design,
- bridge design,
- digital terrain modeling,
- earthwork analysis,

- survey data reduction,
- coordinate geometry,
- horizontal roadway alignment,
- landscape drafting,
- soils log drafting, and
- vertical roadway alignment.

The survey also identified 13 planning and mapping applications accomplished using CADD at state DOTs. They are:

- county maps,
- state highway maps,
- urban highway maps,
- photogrammetric mapping,
- special maps,
- traffic analysis maps,
- district highway maps,
- geographic information system maps,
- cartography,
- planning maps,
- airport utility maps,
- land-use maps, and
- wetlands maps.

Chapter 3 also discusses productivity and cost-effectiveness. It shows that CADD technology must result in at least a 2:1 improvement in productivity over manual techniques in order to offset the additional costs associated with the system. The survey found that most DOTs expected at least a 3:1 productivity improvement when they justified their CADD system purchase.

The survey also found that the most cost-effective design applications on CADD were: (1) roadway design, (2) bridge design, (3) interactive photogrammetric mapping, (4) quantity takeoffs and estimate sheets, (5) automated survey data collection, (6) right-of-way plan drafting, (7) typical sections plan drafting, (8) traffic sign design, (9) architectural drafting, (10) boring logs drafting, (11) county highway mapping, (12) earthwork analysis, and (13) profile design. A 1984 Transportation Research Board (TRB) survey indicated that the average productivity for all application areas was 3.6:1. It follows that using CADD for these applications results in two significant benefits: (a) costs are the same or substantially less and (b) the time required to perform the work is significantly reduced. These benefits are in addition to qualitative benefits such as better drawing quality, increased standardization, greater ease and flexibility in making drafting changes, and more time available to examine alternative designs. The survey found that, on the average, for states using CADD, DOTs did approximately one-half of their design and drafting work on CADD in 1988.

This chapter also treats the subject of requiring engineering consultants to do their designs on CADD. The survey found that only 3 out of 39 DOTs indicated that they have such requirements. Fourteen, however, indicated that they expected that CADD would become a mandatory requirement for consultants in the future.

Finally, Chapter 3 discusses pitfalls in CADD practices. These include: (a) purchasing unneeded software, (b) skimping on hardware, (c) putting inefficient applications on the CADD system, and (d) not adequately specifying the format of a consultant's CADD projects.

Chapter 4 addresses personnel issues. These include: (a) selection and sources of CADD trainees, (b) training, (c) performance evaluation, (d) staffing, (e) compensation, (f) shift work, (g) unions, (h) organizational structure, and (i) pitfalls.

The survey found that the overwhelming majority of DOTs indicated that existing personnel were the primary source of CADD trainees. Most DOTs select CADD trainees based on their desire, aptitude, and productivity, although some DOTs indicated that all of the design and drafting personnel were trained on CADD and that all were expected to employ it as a standard tool in their daily routine.

The survey found that DOTs allow an average of five months for the evaluation of new CADD trainees and that 90 percent have established their own in-house CADD training programs. The survey respondees also indicated that, on the average, 4.8 months are required for a CADD trainee to reach satisfactory production rates.

When evaluating CADD operator performance, DOTs most often use three general factors: (a) productivity, (b) accuracy, and (c) knowledge of the CADD system. However, only about one quarter of the DOTs indicated that standards for productivity were developed and applied. The DOTs indicated that the average turnover among workstation operations was 16.3 percent per year.

Chapter 4 also discusses staffing. The DOTs indicated that, on the average, 75 percent of workstation operators were drafters. More than one-third of all respondents said that 100 percent of their workstation operators were drafters.

With regard to compensation, the DOTs indicated that the average starting rate for workstation operators was $8.30 per hour. Moreover, they indicated that the average maximum pay rate was $14.54 per hour.

DOTs were also questioned regarding their shift-work policies. Sixty percent indicated that they operate their CADD system more than one shift per day. In addition, 56 percent indicated that they offered a pay differential for shift work. Among those who did, the average differential was $0.56 per hour. With regard to unions, 60 percent of the DOTs indicated that CADD workstation operators were unionized.

With regard to organizational structure, TRB found in its 1984 survey that more than half the state DOTs assigned management responsibility for the operation of the computers in a CADD system to the automation and information systems group. On the other hand, 97 percent of the DOTs assigned management responsibility for the operation of the CADD workstations connected to those computers to the technical user areas.

Three pitfalls in personnel issues are discussed. These include: (a) failing to provide adequate training, (b) giving employees with unacceptable performance levels too long a time period in which to improve, and (c) failing to maintain adequate pay scales.

The use of CADD has developed rapidly over the last several years. Computer-aided design and drafting provides important new computer-graphic tools for planning and engineering design functions. It is fast becoming more economical as well as more sophisticated. The following chapters provide information on CADD covering system selection, current practices, and personnel issues and identify the pitfalls that could be encountered in each area. The synthesis concludes with a chapter containing conclusions and recommendations.

CHAPTER ONE

INTRODUCTION TO CADD SYSTEMS

HISTORY

Computers have been used in the civil engineering design profession since the late 1950s. The first applications of computers were for tedious and repetitive calculations such as those required for structural engineering, coordinate geometry, earth work analysis, and floodplain hydraulics. These applications were often FORTRAN programs written for mainframe computers of that era. Input was usually on punch cards and output took the form of data listings on computer paper by printing terminals.

The first computer-graphics applications for civil engineering appeared in the early 1970s. At this time, pen plotters were developed that could draw data on paper much like a "robot draftsman." Graphic information such as survey lines computed using coordinate geometry programs was translated into instructions to the pen plotter that drew the information. These were the first computer-aided drafting systems but they had a severe limitation. To modify the plotted information, the user had to modify the data set being plotted. At first, this was done by modifying the punch card deck. However, even after the advent of video display terminals, users still had to make tedious changes to the coordinates contained in the data set in order to modify the plot. This process required several iterations before the drawing revision was complete because the user could not see the effect of the changes until they were plotted.

Around the middle of that decade it became possible to display coordinate geometry data on a video screen. The video screen was assigned its own coordinate geometry system and it was referenced to the coordinate geometry system of the data set being displayed. Shortly thereafter it became possible for the user to use a screen cursor to identify data points and objects on the video screen. At first this cursor was moved using thumb wheels or joy sticks within the terminal keyboard, but later cursor movement was controlled by moving a pointing device across the face of a sensitized tablet whose coordinate geometry had also been referenced to that of the video screen.

These two developments—the display of coordinate geometry information on a video screen and the ability to point to the information being displayed—made interactive computer graphics possible. The final step required to develop a fully functional CADD system was the development of programming commands to place and edit data using commonly accepted drafting concepts such as "draw a circle of a known radius," "intersect two lines," "copy an element," and so forth.

The use of CADD systems started growing rapidly in the early 1980s. A number of corporations began offering "turnkey" CADD systems. These products included all computer hardware, software, training, support, and maintenance necessary for an organization to adopt the new technology. Early applications of CADD technology included mapping and drafting for civil engineers, structural engineers, mechanical engineers, power and process engineers, and utilities. The earliest CADD programs were created to operate on mainframe computers; however, with the advent of minicomputer technology in the mid 1970s, the cost of turnkey CADD packages dropped significantly. Minicomputer systems were also considerably more compact and easier to transport and install.

By the middle of the 1980s, CADD technology had spawned a major industry. Many applications of CADD were explored and marketed by CADD system vendors. Today users include architects; consulting engineers; every major utility; federal, state, and local governments; the transportation industry; the petroleum industry; the aerospace industry; the automotive industry; manufacturers; interior designers; space planners; cartographers; and graphic artists.

EQUIPMENT

There are five primary components to a CADD system:

- the central processing unit (CPU)
- input devices
- output devices
- data-storage devices
- software

The *CPU* can be either a mainframe computer, minicomputer, or a personal computer. Its function is to execute commands chosen by the user, write and read data files, perform numerous calculations and process data, and translate data files to the images that will appear on the video screen or be plotted by the plotter.

Input devices include keyboards, command menu tablets, digitizing tables, scanner, stereo plotters, and survey data collectors.

The *command menu tablet* is a sensitized surface that can detect the position of a pointing device as the user positions it on the command menu. This pointing device is often called a "cursor." Once the user has defined the layout of the menu and the locations of the various commands, he or she can select a command by pointing to it and depressing a button on the cursor. The command menu tablet is also oriented to the video screen. This enables the user to point to objects on the screen and identify them for editing and to define new data points on the screen when placing additional elements. In reality he or she is only pointing to the command menu, and the computer translates the location of the cursor on the menu to a cross hair that moves about on the video screen.

Often the command menu is placed within or upon a *digitizing table*. This table has a large sensitized surface and operates in a fashion similar to that of the command menu tablet. It is used for tracing drawings into the system. The user attaches the drawing to the table surface and then "digitizes" (traces) lines on the drawing.

A *scanner* is a device that automatically digitizes drawings. It uses an optical system to "read" lines on the drawing and convert them to CADD data.

A *stereo plotter* is used to make maps from stereoscopic pairs of aerial photographs. The stereo plotter can be linked directly to the CADD system so that the map data are digitized as the map is being traced from the photographs.

Survey data collectors are used to capture land survey instrument readings in a digital format. The data collector is then linked to the CADD system and the data are transferred for storage and plotting.

Output devices include video screens, plotters, and printers.

The *video screen* or *monitor* is a cathode ray tube (CRT) similar to a television. It receives signals from the computer and displays CADD drawings for the user. The image is represented by small points of light commonly referred to as pixels. The term pixels is a shortening of the phrase "picture elements." Video screens for typical CADD systems range from 13 in. to 19 in. in diagonal dimensions. Large video screens are available, but costs are excessive at this time.

The *plotter* is a machine used to draw CADD files on paper, plastic film, or other medium. The two basic types of plotters are pen plotters and electrostatic plotters. The pen plotter uses various types of pens to draw. Often the drawing motion is achieved through a combination of moving both the pen and the paper. The electrostatic plotter draws using a thermal process. The image is drawn using dots that may be as dense as 400/in. The higher this density, the better the quality of the plot or drawing will be. A density of less than 100 dots per inch is considered generally unacceptable for engineering quality drawings. Pen plotters generally produce a higher quality of plot but at a usually much slower speed than electrostatic plotters. Laser plotters are also gaining acceptance.

The *printer* is used to transfer information to paper.

Data-storage devices are used to record computer files on magnetic media. These include hard disks, floppy diskettes, and computer tape. The computer writes the data onto the medium and reads them from the medium. These files may contain either programs or data. The programs contain instructions to the computer, whereas the data files contain the information needed for a particular application of a program or the data resulting from the operation of a program. In the case of a CADD system, these data files contain the elements of a map or drawing encoded in a format that is readable by the computer program.

The *software* includes operating system software and applications software. The operating system contains the basic commands needed to control the hardware. These commands include procedures for managing files, security, controlling peripheral devices, and accessing application software. In a CADD system, application software includes the programs used for drafting and design.

CHAPTER TWO

SYSTEM SELECTION AND IMPLEMENTATION

MANAGEMENT SUPPORT

Management support is critical in the success of a CADD operation. Computer-aided design and drafting technology is relatively new to the engineering, drafting, and mapping industries. Moreover, top managers are often senior personnel with little exposure to computer systems in general and almost no exposure to CADD in particular. The CADD operation often depends on a "champion." This is an individual (or a team) within the organization who is actively promoting the use of CADD because of personal interest or previous experience with the technology or who has been assigned the task by senior management. The champion has been asked to investigate CADD and see how it may be applied within the organization. Usually this champion comes from the middle-management levels of either the technical or the computer science disciplines.

This champion often becomes a zealous promoter after he or she has seen the potential that CADD technology has for improvement in quality, better communication, less paper work, and faster production of engineering designs and drawings. However, there is often a great deal of resistance from a number of areas. Top management may offer only token support, with middle management offering no support at all. For instance, if the champion comes from a technical discipline, there may be some resistance from people in the management information systems group, which views all computers as falling within their "kingdom." Because they are considered the experts in computer systems, they may have some reluctance to share their expertise in support of a person who is not a computer scientist.

The CADD champion needs to be reliable, capable, experienced, resourceful, and motivated. He or she needs to be trusted with authority as well as responsibility.

The champion may also find resistance from fellow engineers, drafters, cartographers, and other technicians who are perhaps skeptical and defensive about the introduction of a new technology. This is because a new technology will require significant changes in the way they do their work. This is especially true among older staff members who are faced with the need to learn computer technology for the first time in their careers. They will naturally be reluctant to change from the status quo.

The champion may also encounter resistance from those involved in the budgeting process. This is because CADD systems, especially minicomputer-based CADD systems, are very expensive capital equipment items. Moreover, they are being introduced into engineering, design, drafting, and mapping operations, which typically have been labor-intensive. In the past it cost only several hundred dollars to equip a draftsman or an engineer for the job. However, the advent of CADD technology requires a per capita investment of tens of thousands of dollars. This has a significant impact on the organization's budget.

Any one of these factors can make the CADD champion's job a difficult one. If the specific charge by top management is to investigate and, if justified, implement CADD technology, the job will be easier. If the champion is promoting CADD on his or her own and has found no "believers" among top management, the job is nearly impossible until there are some converts in the upper ranks.

To provide effective support, top management must provide a clear definition of the CADD program's objectives. It also means listening to new concepts with an unbiased and open mind. It means lending encouragement to the CADD champion when things move more slowly than had been expected. It means taking reasonable risks on investments in new technology that are not totally guaranteed to pay off. And, it means making short-term financial and production sacrifices for long-term financial and qualitative benefits. A written plan will greatly help the organization to stick to top-priority applications. Finally, management support must be continuous over the long term.

REQUIREMENTS ANALYSIS

The acquisition and implementation of CADD systems usually represent a substantial investment in capital, personnel time, and organizational resources. Most organizations have well-defined procedures for justifying and evaluating capital investments. Usually these are called a "needs assessment" or "requirements analysis." Although each organization usually has its own approach, a typical requirements analysis contains the following elements:

- *Current Process* This is an examination of the existing techniques, methods, procedures, equipment, and personnel used to accomplish the organization's engineering design, drafting, and mapping missions. It is an objective statement of how the work gets done today.
- *Current Costs* This is an evaluation of what it currently costs the organization to accomplish its engineering design, drafting, and mapping missions using the existing process. Cost items that need to be documented include salaries and benefits (for both production and supervisory personnel), office space, supplies, equipment and furnishings, telephones, computers, training, storage, and so forth. There may be a cost associated with *not* having CADD because of the turnover in personnel who want to work with current technologies.
- *Potential Applications* This phase requires the knowledge of an individual who is familiar with CADD applications because

of previous experience or because he or she has set out to learn about them. This individual will review the existing process and use previous experience with CADD to identify those areas in which CADD technology may be of benefit. The result will be a clear statement of how CADD technology may be used to supplement, augment, or replace portions of the existing process.

• *Expected Costs* This is an assessment of what it will cost the organization to purchase, implement, maintain, and develop CADD technology. The *purchase cost* of the CADD system should include all hardware and software products, delivery and installation charges, and the labor cost involved in attending acceptance tests. It is important to carefully review the list of expected hardware and software purchases to ensure that no items are left out. It is best to obtain a quotation from several vendors for a typical system installation.

Implementation Costs should include initial employee training, establishing CADD standards, space renovation, air conditioning, power conditioning, and the cost of converting standard details and drawings to a library of CADD standards. A review of implementation and maintenance costs is especially important, because these costs are often overlooked or wrong.

Maintenance Costs should include the vendor's maintenance contract, ongoing employee CADD training costs, and the cost of computer science personnel needed to support the system. These support costs include both the operation of the computer and peripheral devices as well as support to CADD users. Experience has shown that user support and training costs are significant. *Miscellaneous costs* should also include supplies, such as computer tapes, plotter paper, ink and pens, etc.

Development Costs include refinements to and customization of the software to better suit user needs. Software upgrades must be included as well.

• *Potential Benefits* This is a statement of how CADD will benefit the organization. It must be made in specific, clear terms with as few general statements as possible. There are usually three types of benefits: (a) cost displacement, in which existing costs are reduced or eliminated, (b) cost avoidance, in which future costs are reduced or eliminated, and (c) value added. This last type of benefit represents those less tangible items, such as "the ability to look at more design alternatives," "shorter production schedules," "better organized drawing storage," "improved drawing quality," "job enrichment," "better coordination among technical disciplines," etc.

• *Payback Analysis* Each organization will also have its own technique for expressing the economic justification of a capital investment. Sometimes this takes the form of a "return on investment" calculation, a "payback analysis," or a "cost-benefit ratio." Most important, this is a statement that justifies a significant capital expenditure in economic terms.

One of the questions asked in the survey conducted for this synthesis concerned the anticipated cost-effectiveness of CADD before purchase. Out of 39 responses, slightly more than half expected a 3:1 productivity improvement upon purchasing the CADD system. That is, by using CADD, production times would be one-third of their current levels without CADD. An additional 30 percent expected a 2:1 improvement in productivity with the advent of CADD. Therefore, more than 80 percent of the users surveyed expected that their production times would decrease by at least one-half.

VENDOR SELECTION

The process used to select a vendor to supply the CADD system is very important. The type of system selected, its capabilities, its price, and its features will directly affect the success of the entire CADD operation. The issue is very complicated. Many questions need to be answered, such as: Which vendor's system will yield the highest productivity improvements? Which system will be least expensive considering *all* costs, not just the purchase price but also ongoing maintenance and support charges? Which vendor is most likely to be around over the long term so that future support is assured? Which vendor has the most systems installed that are similar to the application in question and, therefore, is the most experienced at solving its problems? Which vendor's hardware and/or software is most reliable? How quickly will the vendor respond to software and hardware problems? Which vendor is committed to continuing development of hardware and software offerings? Which system will be easiest for the operating personnel to learn? What claims regarding performance and future enhancements are credible? What options exist for exchanging data with other CADD system formats?

The responsibility for vendor selection is most often shared between the computer systems department and the technical departments, such as engineering, drafting, and mapping. Usually a selection committee is formed that includes representatives of the computer systems department as well as each of the technical user areas. Most state procurement regulations also require that representatives of the contracts, accounting, and/or finance departments participate in the selection process as well. In the survey taken for this synthesis, the vast majority of the state DOTs emphasized selection of a vendor based on technical qualifications as opposed to selection of a vendor based solely on a low bid. Nonetheless, about half indicated that they first made a selection based solely on technical qualifications then negotiated the purchase price, whereas the other half said they used a combined process in which they evaluated both the vendor's technical qualifications and bid using weighing factors.

Approximately half said they required that the vendor or vendors conduct performance ("benchmark") tests before the selection. A benchmark test is a live test demonstration of a vendor's system using a real design drafting task. It is usually evaluated carefully in order to compare the results of several vendors' benchmarks. This is understandable in view of the complicated issues involved, the constantly changing state of the art in hardware and software technology, and the fact that CADD is a new technology for the first-time buyer. Benchmark tests also provide an objective measure of system performance that can be used to evaluate vendor claims. Moreover, the system purchase has usually been justified on the basis of certain assumptions regarding productivity improvements in design and drafting. Although productivity improvements will not be significant until libraries are built, benchmarks may provide a basis for substantiating these expected productivity improvements. Important evaluation factors are software compatibility, equipment configuration, speed, and output results.

Most often a request for proposal (RFP) is prepared and provided to prospective vendors. The RFP defines as clearly as possible the objectives of the procurement, the equipment and software to be procured, the specifications regarding system performance, schedule of delivery, contract terms and conditions, and so forth. It should allow for improvements in technology during the procurement cycle. Responses in the form of proposals by the vendors are evaluated by members of the CADD selection committee. Each member is asked to evaluate proposals, usually employing a numerical ranking system to evaluate factors such as vendor experience, equipment performance, and software features. As mentioned above, about half of the DOTs surveyed include cost in this evaluation process.

SYSTEM COSTS

One of the most remarkable changes in CADD systems since the beginning of the 1980s has been the dramatic drop in the cost of CADD equipment. This drop parallels the reduction of most automated data-processing equipment over the same period of time. This fact is even more phenomenal considering the tremendous increases in equipment performance that have also occurred. These performance increases have been seen not only in the computing speed of the CPU, but also in the capabilities and features of peripheral CADD devices, such as workstations, display terminals, plotters, and data-storage devices.

In December of 1982, the average cost per graphics terminal of installed CADD systems was $144,600 for minicomputer-based CADD systems. In 1983, this figure fell to $138,000, and in 1984 the figure was $119,500, according to surveys conducted by TRB in 1982, 1983, and 1984 (*1*). In 1988, this figure fell to $76,200, according to the survey conducted for this synthesis. This is an average decrease of 10 percent per year from 1982 to 1988.

One must bear in mind that these figures are taken from survey questionnaires answered by DOTs with installed CADD systems. Therefore, the figures included relatively new equipment purchased shortly before the survey as well as older, more expensive equipment purchased several years before. CADD equipment is never *functionally* obsolete provided replacement parts and maintenance support are available, although these items may become too expensive to justify. On the other hand, CADD equipment becomes *technologically* obsolete quite rapidly, often before it is delivered to the customer. This has been because of the rapidly advancing state of the art in computer equipment technology. Nonetheless, most equipment can be used at least five years or more before it is either traded in, sold, or discarded.

Therefore, one may want to examine price per CADD workstation for new equipment over the same period of time. In 1982, a typical CADD system consisting of a VAX 11/750 CPU, six workstations, an electrostatic plotter, two hardcopy plotters, two 300 Mb disk drives, a system console, a tapedrive, and an alphanumeric terminal cost approximately $650,000, including taxes, insurance, delivery, and installation charges. The cost per workstation was therefore about $109,000.

In 1988, a typical CADD system with 10 graphics workstations would cost around $600,000. This is a cost per graphics terminal of about $60,000. Moreover, the disk drives would be much faster and the user would now be able to "download" the drawing file to the workstation for faster screen updates and higher productivity. This is an average decrease in the cost per workstation of about 10 percent per year.

Although these falling prices for minicomputer-based CADD system equipment have been remarkable, another significant phenomenon has occurred since 1985 with the advent of "PC CADD." As personal computer systems gained speed and capacity during the first years of the 1980s, several vendors developed software programs that enabled the personal computer to be used as a CADD workstation. This software featured many of the standard two-dimensional drafting commands previously available only on the much more expensive minicomputer systems. Although the speed and capacity of the PC was limited relative to the minicomputer system, the single PC user still had much of the capability needed for small drafting projects. The significance of PC CADD lies in the fact that the PC-based workstation, including the CADD software and a command menu tablet, could be set up for less than $15,000.

During the early 1980s, this phenomenon gave engineers and drafters access to the CADD technology at a relatively low cost. This resulted in a proliferation of CADD applications. Because the minicomputer-based systems were relatively expensive, they were usually purchased only by the larger engineering firms, government agencies, and universities that had a budget large enough to absorb the cost. On the other hand, PC CADD made CADD technology affordable to smaller engineering and architectural firms, government agencies, universities, and even to individuals. It first appeared as though PC CADD represented "CADD for the common man"; however, it was not long before even the larger organizations, even those who had already purchased minicomputer-based CADD systems, saw that they could increase the number of their CADD workstations at a much lower incremental cost while still being able to perform most of their standard two-dimensional drafting tasks.

Despite these cost advantages, the first PC CADD users found that there were severe limitations on the work they could do. As drawing files became larger, the PC took much longer to respond to commands. When a CADD workstation does not respond to a user's command relatively quickly (within about 3 sec), the user tends to grow frustrated and impatient. Moreover, CADD operation frequently requires that the system repaint the entire drawing on the screen. When the drawing file is small and contains only a few dozen elements, even the first PCs (based on the 8088 microprocessor) would display an entire drawing in a matter of a few seconds. However, as drawing files grew to contain thousands of drawing elements, the standard PC could take a minute or more to display a drawing. The addition of hard disk drives on the PC/AT type of machine improved the system response somewhat. The advent of the clock speed and data bus associated with the 80286 processor improved response to an acceptable level for many projects. However, it was not until the introduction of the 80386 processor in 1986 that PC CADD became a realistic option for most civil engineering design and drafting applications.

In mid 1989 a typical PC CADD software program performed nearly all of the standard two-dimensional drafting operations that a minicomputer CADD system offered and many PC CADD software programs offered substantial 3D drafting capability as well. There were still some serious disadvantages and limitations to PC CADD, however. The first limitation lay in disk storage capacity of the PC relative to a minicomputer. A PC hard disk in a standard configuration, for instance, typically held 20 to 60 megabytes of data, whereas a minicomputer disk drive held on the order of 300 to 600 megabytes of data. Personal computer hard disks holding 300 megabytes are now commonly used in network file servers, however, making networking a feasible option. Large hard disks may soon become common for individual PCs as well.

A second limitation lies in the area of applications. Minicomputer-based CADD software has been developed over the past two decades and includes a wide variety of special applications for specific engineering and drafting disciplines. PC CADD, on the other hand, is still somewhat of a generic tool, although special applications for specific disciplines are being developed rapidly and are appearing on the market monthly. Nonetheless, more special application programs are available for minicomputer-based systems.

Another disadvantage of PC CADD is that the buyer has more work to do to gather the information needed to make a decision. PC CADD can also be restricted if the user operates a large number of workstations and needs to exchange drawing information between them. Files are distributed among all users. At first, it was necessary to do this by copying files on floppy disks. This created tremendous logistical and storage problems. In the last several years, however, PC networking has helped reduce this problem. It is now possible to link a number of PC workstations, producing a multiuser environment similar to that of a minicomputer supporting a large number of workstations. Nonetheless, file management and security can still be major problems today when using a PC CADD network.

One of the significant advantages of PC CADD is the fact that the user is assured of consistent response from the CPU. Minicomputer-based CADD users quite often complain of system response time when the system is being used at capacity. This is because all users are competing for one CPU resource. With PC CADD each user has a CPU resource. Even though that CPU may be slower than the minicomputer CPU, the user no longer has to share that single resource with a number of other users.

In the last few years, "engineering workstations" have received increasing attention by CADD users. Engineering workstations offer the advantages of lower cost and dedicated CPU resources for individual users that personal computers afford but also offer the processing speed and storage capacity advantages that minicomputers and mainframe computers have offered in the past. Their prices generally lie between those of personal computer systems and minicomputer systems, yet they offer CPU processing speeds that rival those of minicomputer systems. Engineering workstations are usually based on the UNIX operating system, which offers the further advantage of multitasking processes. Multitasking refers to a CPU that is performing more than one task at the same time. Personal computers operating under DOS typically perform one task at a time. During the course of preparing this synthesis, the California Department of Transportation announced that it had acquired 346 engineering workstations for roadway design and expected to have 800 workstations by the end of 1989.

Maintenance is another significant cost of owning a CADD system. Many vendors offer a standard comprehensive maintenance agreement that covers both hardware and software support. A generally accepted standard of the computer equipment manufacturing industry is to charge approximately 10 percent of the hardware purchase price for annual maintenance. Thus, in 1982 the typical CADD system consisting of a CPU, six graphics terminals, and necessary peripherals cost about $650,000 to procure and approximately $65,000 per year to maintain. On the other hand, the typical 1988 CADD system consisting of a CPU, 10 graphics terminals, and necessary peripherals would cost approximately $600,000 dollars to purchase and $60,000 per year to maintain.

Two other types of maintenance costs are those for training and development. As will be shown later, a CADD operator typically requires two to six months to reach a satisfactory level of productivity. This "learning curve" cost is in addition to approximately 40 hours of initial instruction. Moreover, there is a steady turnover in CADD operators, requiring continuous training of replacement personnel. These facts often dictate that a permanent staff of CADD trainers be added to the organization.

As the CADD system is used more extensively, users often find procedures or new applications that existing software cannot address. This requires modification of existing software or development of new software. Moreover, vendors improve their software and release new versions. Some new versions incorporate significant changes in operation. For these reasons, installing new software releases can require significant development efforts

These costs for procuring and maintaining CADD equipment are important because they largely dictate the budget allocations required to establish and operate a CADD system. Conversely, a given CADD budget will dictate how much equipment can be procured.

SYSTEM IMPLEMENTATION

The key to successfully implementing a CADD system is to develop a sound plan and stick to it unless the overall scope and objectives are revised. This plan should include the following elements:

- *Goals* This is a statement of the general objectives of the implementation program. It might cover considerations such as which users will be trained on the system, what projects will be accomplished using the system, what application areas will be given access to the system, what productivity improvement is expected, and so forth.
- *Schedule* The schedule should begin at a point well in advance of the actual installation of the equipment. A good place to begin might be the vendor's acceptance of the purchase order. The purchase order should cover every key step, including acceptance tests, developing plans for space renovation, accomplishing the renovation, system delivery, system management, operation training, user training, creating libraries of standard details and drawings, initial project applications, and periodic productivity assessments.
- *Milestones* The implementation plan should identify tangible and measurable goals that are key to measuring the progress and success of the CADD program. These milestones might include: system delivery, user training, and completion of the first CADD project. At each of these milestones senior management should be required to give approval of the progress thus far before continuing with the implementation plan.
- *Required Changes* As pointed out above, CADD technology represents a significant departure from established and traditional ways of performing engineering design, drafting, and mapping. Such a radical departure from established practice will often dictate changes in organizational structure, lines of communications, and areas of responsibility. These should be antici-

pated and included in the implementation plan. Computer-aided design and drafting drawing standards must be determined and enforced so that the "final" plans are acceptable to all concerned.

For instance, it may be a traditional function of the photogrammetry department to compile a pencil-on-mylar manuscript depicting planimetry and topography for a project site without doing the final drafting of the base sheet. This may be the function of a separate drafting department. However, after linking photogrammetric stereo plotters directly to the CADD system, it is desirable to fully train photogrammetrists in the use of the CADD system and require them to compile data as a "final" map product that needs no further drafting enhancement or correction.

As another example, it is desirable to train engineering design personnel in the use of the CADD system in order that they may make final corrections to CADD drawings instead of following the traditional practice of marking a print in red and turning it over to a draftsman for correction.

This implementation plan needs to be reviewed and revised, if necessary, at regular intervals. A five-year plan, for instance, may need to be updated at least every year. The 1984 TRB survey (*1*) found that 42 percent of the 48 users responding indicated that the computer/automation department had management responsibility for the implementation of CADD systems, whereas 29 percent of the users indicated that the design department had that responsibility. The remaining 29 percent of the users indicated that this responsibility had been assigned to another technical area such as drafting, photogrammetry, mapping, or planning.

SYSTEM OPERATING COSTS

There is yet another important cost figure that must be considered, the hourly cost of operating the system. This figure expresses the CADD system's cost-effectiveness using a unit that is familiar to the engineering, drafting, and mapping manager. The cost of engineering design and drafting is most often expressed in terms of manhours and hourly wage rates for various categories of engineering and technical personnel. Because CADD systems are thought of as productivity improvement tools, it is useful to consider the hourly cost of operating the CADD system relative to the hourly labor savings that it produces.

Chapter 4 discusses the use of multiple shifts on the CADD system. Approximately half of the state DOTs run their CADD systems on a two-shift-per-day basis, with the other half operating only one shift per day. In TRB's 1984 survey (*1*), state DOTs indicated that they use CADD workstations an average of 11.3 hours per day. This is in line with the author's observation that in a typical CADD operation, each graphics terminal will be actively used between 25 and 30 hours per week per shift. Assuming a two-shift-per-day operation, this equates to 50 to 60 hours per week (10 to 12 hours per day) per workstation. The lower figure will be used to account for training, development, and other "indirect" production uses. It is assumed that the purchase is amortized over five years, the annual maintenance cost is 10 percent of the purchase cost, and eight full-time personnel are required to provide system management and system operation support. It is also assumed that supplies will cost $1,000 per workstation each year; space rental will cost $2,000 per workstation each year; utilities will cost $500 per workstation each year; and two workstations will be devoted to training, system support, and system research and development. These figures are based on "1988 CADD Application and User Survey" conducted by *PSMJ Magazine* (*2*). Finally, it is assumed that 10 days of annual leave, 5 days of sick leave, and eight holidays will reduce the number of days available for operations from 260 (52 weeks × 5 days per week) to 237. The hourly cost of operating a 20-workstation system can be derived as follows:

20 workstations × $76,200 per workstation = $1,524,000 purchase cost

$1,524,000 ÷ 5 = $304,800 annual depreciation charges

$1,524,000 × 0.1 = $152,400 annual maintenance charges

8 personnel × $25,000 average annual salary = $200,000 annual salary charges

$200,000 salaries × 0.5 = $100,000 annual employee benefits charges

$1,000 per workstation × 20 = $20,000 annual supply charges

$2,000 per workstation × 20 = $40,000 annual space rental charges

$500 per workstation × 20 = $10,000 annual utility charges

Total annual charges = $827,200

10 hours per day × 18 production workstations × 237 days per year of operation = 42,660 hours per year of production

$827,200 ÷ 42,660 hours of production = $19.39 per hour cost of production time excluding operator costs.

If the same assumptions were made, except that the system was run only one shift per day, obviously the cost would roughly double to $38.78 per hour. (It may be slightly lower. Fewer support personnel would be required and the hours of actual production on a typical shift may increase in a one-shift operation.) These figures should be kept in mind for the discussion of Productivity and Cost-Effectiveness below.

PITFALLS IN SYSTEM SELECTION AND IMPLEMENTATION

In preparing this synthesis, the following issues were identified as being most critical and most often omitted during the process of CADD system selection and implementation:

- *Failure to obtain top management support and understanding of the CADD program*. This most often results in program stagnation. The program gets off the ground, but just barely. After an initial equipment purchase, no further purchases are authorized. User demand often outstrips initial system capacity, resulting in a frustrated user group. This is also frustrating for the CADD champion, who sees the great benefits of the CADD program but feels he or she is receiving little or no recognition for efforts in support of such a program. This also produces frustration on the part of senior managers, who want to believe their investment was worthwhile but haven't yet seen the results that prove it was. Often, the senior managers are either unfamiliar with computer technology or uninformed as to the progress that has been made. They then grow impatient with the CADD program, its apparent lack of results, and its continuing expense.

• *Failure to plan*. The old proverb "If you don't know where you are going, any track will get you there" could never be more true than when implementing a CADD system. The potential for application is almost unlimited, yet there are definitely certain applications that are more productive and more cost-effective than others. (These are discussed more fully in Chapter 3.) This presents the very real danger of employing the system in a manner that does not yield the greatest possible results. In fact, it is entirely possible to use the CADD system on some projects and find that it has cost more than if traditional manual design and drafting techniques had been used. Some of this knowledge is gained only by experience; nonetheless, a well-thought-out implementation plan may avoid many of these unsatisfactory applications.

Failure to plan also means failure to provide an adequate yardstick for measuring progress. This robs the CADD champion of a sense of accomplishment for the progress that has been made. It can also be a contributing factor in his or her failure to obtain or maintain top management support.

• *Failure to anticipate all costs*. Selecting and buying CADD equipment, especially peripheral items such as disk drives, tape drives, terminals, plotters, and communications hardware, is like sailing in uncharted waters for most engineering, drafting, and mapping managers. Even with the aid of computer systems support personnel, it is very likely that some items will be left out of initial budget requests. Unfortunately, this is usually discovered after the budget has been approved and a purchase order has been submitted to the vendor. Sometimes, it is not discovered until the system has been installed. Initial meetings with sales representatives to develop approximate cost figures may have overlooked some items, and additional purchases become necessary. Similarly, sometimes not all indirect costs, such as training, software upgrades, initial productivity losses, and user support, are fully anticipated. This can be a great source of irritation to top managers, who may find good reason to ask, "Where will it all end?"

• *Failure to set reasonable expectations*. Computer-aided design and drafting systems have received a great deal of publicity regarding increased drafting and design productivity. Computer-aided design and drafting systems most often meet or exceed these expectations, so that is not an issue here. What users and managers often fail to anticipate is the length of time needed to achieve these productivity gains. A design or drafting technician typically requires up to six months to reach a satisfactory level of productivity. Considering the fact that with a new system all users are new users, it certainly follows that at least six months will be required before a new CADD operation starts producing at satisfactory levels. Moreover, user support staff must be trained and libraries of standard details and symbols must be created. On the other hand, there is a tendency for managers and users to expect to achieve great results immediately after the system "comes out of the box."

• *Failure to provide a capable systems support staff*. Most CADD systems need to be customized in order to meet each user's particular requirements. Vendors provide a basic software package that can be used "as is" with moderate success. However, the greatest potential lies in customizing that software package to meet the needs of a particular application. This most often involves the creation of custom command menus, libraries of standard drawings and details, and user "macro" commands that link together a number of basic CADD system commands in one operation. The combination of these programming devices enables the user to gain the greatest productivity enhancements from the CADD system.

An experienced and capable programming staff is needed to develop these customized programs. Without them, the CADD system can be very much like a V-8 engine operating on only four cylinders. In addition, a support staff must be available for troubleshooting, training, software upgrades, file backups and archiving, daily system operation, and so forth.

CHAPTER THREE

CURRENT PRACTICES

GENERAL APPLICATIONS

Based on the survey conducted for this synthesis, the principal types of applications of CADD at state DOTs are the following:

- Roadway design and drafting
- Bridge design and drafting
- Interactive photogrammetry
- Automated survey data collection
- Mapping

These general types of applications are briefly described below.

Roadway design and drafting has benefited from computer technology since the 1970s. First applications were the creation of programs to speed tedious and highly repetitious earthwork and coordinate geometry calculations. These first programs ran in a batch mode using punch card or tape input and resulted in tabulations on standard computer paper.

With the advent of pen plotters it became possible to plot profile and cross-section lines as well as vertical and horizontal geometry. New design and computational features were steadily added until the horizontal and vertical design process could be nearly entirely done using the computer. With the 1980s, interactive CADD systems linked to roadway-design programs made it possible to accomplish nearly the entire design and drafting process using the computer. Today's roadway-design systems can compute and plot horizontal and vertical roadway alignments; reduce, store, modify, and plot terrain data; perform geometric calculations; store and plot resulting layouts; design roadway templates, medians, special ditches, and slopes including benched slopes; compute earthwork quantities for multiple roadways; plot interchange layouts, ramp merges, and right-of-way lines; store design criteria and calculations for further processing; perform bridge-geometry calculations; define and plot planned views of roadways; create and plot perspective views of roadways; and prepare and print design data listings and staking notes (*3*). Some CADD systems create a three-dimensional model of the earth's surface [commonly called a digital terrain modeler or (DTM)] that is used by the various design routines for vertical alignment, earthworks computations, cross-section plotting, and profile generation.

Bridge design and drafting can also be performed using CADD systems. A typical CADD bridge program enables the user to enter geographic superstructure or substructure data when prompted. The design and analysis computation routines are done interactively as the information is entered and can be completed in minutes. A large number of design detail drawings that can automatically be drawn to scale are already available in the system. This allows the user to test several alternatives and document selected designs for easy transfer to a set of plans. When completed, the design can be plotted using standard CADD system commands. Cost estimates can also be produced by entering price data (*4*). Bridge-design software can determine bending properties, compute deadload effects, and locate regions of noncomposite action. Programs will also compute maximum deadload and liveload forces along each bridge span. Users can select from a variety of vehicle configurations and loadings to compute bridge-girder dimensions and tabulate concrete and steel material quantities (*5*). As of the writing of this synthesis, however, bridge-design software is generally behind roadway-design software in its capability to provide a complete design solution.

Photogrammetry is the science of making drawings or maps from aerial photography. The aerial photography has usually been marked with control points that relate to physical monuments or targets placed on the ground before the photography. These monuments have been surveyed and related to an xyz coordinate system. In the past, photogrammetry produced maps by first making a pencil-on-plastic-film manuscript. This pencil manuscript was then redrafted in final format using either scribing or pen-and-ink techniques. With the advent of CADD systems, the pencil-on-film manuscript was manually digitized into the CADD system at large digitizing tables. Computer-aided design and drafting systems have now been linked to photogrammetric stereo plotters using electromagnetic counters. These counters transmit to the CADD system the electronic pulses that describe the movement of the stereo plotter mechanism. In this way, it is possible to plot from the aerial photographs directly into the CADD system, bypassing the traditional pencil-on-film manuscript and final inking. Once the map has been directly digitized into the CADD system by this process of *interactive photogrammetry*, it is possible to make the final plot of the map similar to any other drawing or map plotted by the CADD system. It is also possible to use the topographic and planimetric map information as the base for design work.

Automated survey data collection represents a significant change in the way field survey data are gathered. In the past, survey field crews kept detailed notes by hand, using notebooks. These notes were generally brought into the office, and either the survey crew or a separate specialized office surveyor translated the notes into a more usable format. This process of "breaking down" the field notes involved calculations and plotting the field data in order to graphically represent the survey and mathematically compute its results.

In an automated note-collecting operation, the field crew works with a data recorder that has been linked to the survey equipment. Field measurements are automatically fed to and recorded by the data recorder. In addition to these measurements, the field crew also sends code information to the data recorder indicating what measurements are being taken, what objects are being measured, and so forth. The data collector is then returned to the office and linked directly to a computer system, usually a CADD system, and the data are transferred to the computer. The computer then performs the computations necessary to make the final calculations of the measurements as well as place the data in a CADD file. The data may then be used in the same way as other CADD data for design and drafting applications. Manually taken field notes are reduced to a minimum. Planimetric data can also be recorded and graphics files automatically generated without manual plotting.

Mapping is a process of describing the earth's features on a planar surface. Traditionally this planar surface has been a sheet of paper or drafting film, but with the advent of computer graphics, this planar "surface" is a mathematical model stored as a digital data base in a computer.

State DOTs use computer-graphics technology for two primary mapping applications: computer-aided cartography and geographic information systems (GIS). Transportation agencies usually maintain and publish a series of maps showing the state's transportation network. These include county maps, urban area maps, and specialized maps. In the past, these have been drawn using manual techniques such as inking on mylar and engraving on scribecoat.

Computer-aided cartography relies on CADD technology to produce these maps. Existing maps are usually traced into the CADD system (digitized) by hand. In some cases, they may also be scanned by light-sensitive devices that automatically read and digitize the image on the map. This digital map can then be drawn using pen plotters, electrostatic plotters, scribing plotters, or laser plotters. The graphic quality rivals that of manually scribed maps. Because of the powerful editing capabilities of the CADD system, map production can be much more efficient using it than using traditional manual processes.

A GIS is similar to a CADD system applied to cartography in that it stores geographically referenced data. However, the structure of its data is different. Data in a GIS are organized to facilitate spatial analysis. This type of analysis is useful to resource managers. In a GIS, spatial relationships among data elements are defined. This convention, known as data topology, is a means of describing not only the geometry of linear map features, but also how linear map features are connected, how areas are bounded, and which areas are contiguous. As in a computer-aided mapping system, all map geometry in a GIS is related to a geographic coordinate system. But unlike a computer-aided mapping system, which defines map features as lines or symbols, a GIS defines map features as nodes, lines, and areas.

Nodes represent intersection points and the end points of lines. Each node is uniquely numbered and is located by a pair of xy coordinate values.

Lines are uniquely numbered and their geometry is described by a series of coordinate pairs. A straight line may be defined by two coordinate pairs, whereas additional coordinate pairs are needed to represent curvilinear features. As more coordinate pairs are used, the geometric definition of the line becomes more precise. Lines are also encoded with a beginning node number and an ending node number as well as the area to their left and the area to their right.

Areas are also uniquely numbered and are defined by the lines that form their boundary.

SPECIFIC APPLICATIONS

The survey conducted for this synthesis asked DOTs to indicate "engineering design functions accomplished on the system." Fourteen engineering design functions were identified. These are worth noting here because one of the main purposes of this synthesis is to make the reader aware of the various potential applications of CADD. These engineering design applications are:

- roadway drafting (23 responses)
- bridge drafting (6 responses)
- generating cross sections (5 responses)
- traffic analysis (3 responses)
- architectural design (2 responses)
- bridge design (2 responses)
- digital terrain modeling (2 responses)
- earthwork analysis (2 responses)
- survey data reduction (2 responses)
- coordinate geometry (1 response)
- horizontal roadway alignment (1 response)
- landscape drafting (1 response)
- soils log drafting (1 response)
- vertical roadway alignment (1 response)

By far the most popular application was roadway drafting, followed by bridge drafting, generating cross sections, and traffic analysis.

The 1988 survey also asked DOTs to indicate "planning and mapping areas accomplished" on CADD. Thirteen application areas were indicated in the survey responses. These included:

- county maps (13 responses)
- state highway maps (12 responses)
- urban highway maps (7 responses)
- photogrammetric mapping (6 responses)
- special maps (6 responses)
- traffic analysis maps (4 responses)
- district highway maps (3 responses)
- geographic information system (3 responses)
- cartography (2 responses)
- planning maps (2 responses)
- airport utility maps (1 response)
- land-use maps (1 response)
- wetlands maps (1 response)

There is probably some overlap between certain areas, such as between cartography and state highway maps and between geographic information system and several other mapping categories. The most popular mapping applications were county maps and state highway maps.

HARDWARE IN USE

In the survey conducted for this synthesis 30 out of 39 respondents (77 percent) indicated that the vendor of their CADD system was Intergraph. The vendors for the remaining nine respondents were Hewlett Packard, McDonnell Douglas, Tektronics, Diginetics, Autotrol, IBM, Apollo (now part of Hewlett Packard), and AutoCAD. This closely matches the results of the 1982 TRB survey (*1*), which found that 82 percent of the respondents were using Intergraph CADD systems. Table 1 presents a summary of the responses to questions regarding the numbers and types of CADD equipment items in use at state and provincial DOTs. This breakdown includes the number of CPUs, tape drives, workstations, alphanumeric terminals, pen plotters, and electrostatic plotters and the disk capacity of each installation.

PRODUCTIVITY AND COST-EFFECTIVENESS

In Chapter 2, under "System Operating Costs," it was determined that a graphics terminal will cost approximately $19.39 per hour to operate on a two-shift-per-day basis. According to *PSMJ*, the average total compensation for professional designers is $17.31 per hour and the average total compensation for draftsmen is $10.10 per hour (*2*). (Chapter 4 will discuss the results of the survey conducted for this synthesis regarding salaries for CADD workstation operators.) Assume a draftsman is paid $10.10 per hour. Also assume that the overhead for fringe benefits is 50 percent of that salary ratio. Thus, $15.15 per hour is the total cost of his compensation. If the CADD system is being used two shifts per day, then the work at the CADD workstation will cost an additional $19.39 per hour, for a total of $34.54 per hour. Thus, the work that was previously done at a cost of $15.15 per hour now cost almost 130 percent more. It follows that using CADD must result in a 2:1 productivity improvement to break even. The draftsman must be able to do the work in about one-half of the time that was required using traditional manual drafting techniques. This evaluation does not consider the value of labor saved or options considered when designers use the CADD system.

As mentioned above, 35 out of 39 respondents said before purchasing their systems they expected productivity increases of at least 2:1 and more than half expected increases of at least 3:1. Respondents to the 1988 TRB survey indicated that the "most cost effective design applications" on CADD were the following:

- roadway design (16 responses)
- bridge design (11 responses)
- interactive photogrammetric mapping (6 responses)
- quantity takeoffs and estimate sheets (6 responses)
- automated survey data collection (5 responses)
- right-of-way plan drafting (4 responses)
- typical sections plan drafting (3 responses)
- traffic sign design (2 responses)
- architectural drafting (1 response)
- boring logs drafting (1 response)
- county highway mapping (1 response)
- earthwork analysis (1 response)
- generating profiles (1 response)

The 1984 TRB (*1*) survey indicated that the average productivity for all application areas was 3.6:1. Respondents were requested to estimate the productivity improvement for 29 applications areas. The results were as follows:

Application Area	No. Responses	Avg. Ratio
Building design	1	10.0:1
Business graphics	2	6.5:1
Land use mapping	2	6.5:1
Architecture	1	6.0:1
Accident analysis	1	5.0:1
Hydraulic design	1	5.0:1
Mass transit planning	1	5.0:1
State planning	2	4.5:1
Urban area planning	2	4.5:1
Regional planning	1	4.0:1
Right-of-way design	1	4.0:1
Traffic design	4	3.8:1
Drafting	17	3.6:1
Review plots	2	3.5:1
Right-of-way mapping	4	3.5:1
County mapping	8	3.4:1
Urban area mapping	7	3.4:1
Bridge design	10	3.3:1
Design mapping	6	3.3:1
State mapping	4	3.3:1
Traffic engineering	3	3.3:1
Roadway mapping	5	3.2:1
Thematic mapping	1	3.0:1
Roadway design	9	2.8:1
Stereo digitizing	9	2.6:1
District mapping	1	1.5:1

If the system is amortized over three years, as some experts argue, productivity needs to exceed 2.71:1 to be cost-effective. The ratios above show that at this breakpoint practically all the application areas would still have significant benefits. It follows that using CADD for these applications results in two significant benefits:

- Costs are the same or substantially less;
- The time required to perform the work is significantly reduced.

Another indication of productivity and cost-effectiveness is the amount of work that is actually done on CADD. In the survey conducted for this synthesis, 33 respondents indicated how much of their design and drafting they accomplish using CADD. The responses ranged from 5 percent to 95 percent. On the average, the respondents said that 47 percent of their design and drafting was accomplished using CADD. Clearly there must be a significant benefit from CADD for it to gain such acceptance.

REQUIRING CONSULTANTS TO USE CADD

A large number of consultants to state DOTs use CADD systems to accomplish their design and drafting work. After the consultant has completed the project, the design drawings are often referred to, copied, or modified by the DOT for subsequent projects. As stated previously, the average state DOT uses CADD for nearly half of its design and drafting work. Therefore,

TABLE 1
SUMMARY OF SURVEY RESULTS

Organization	Vendor[a]	Installed	Initial Cost ($)	Current Investment ($)	No. CPU	Disk Capacity (MB)	Tape Drives	Work Sta.	Alpha Term.	Pen Plot.	Elec. Plot.
Alabama Highway Department	IGH	3/01/87	1,039,450	1,780,000	1	1100	1	17	11	3	7
Alaska DOT & PF	TTX	8/01/84	60,000	150,000	1	300	1	3	0	1	0
Arizona Dept. of Transportation	IGH	2/01/86	1,600,000	3,000,000	2	3374	2	26	14	2	3
Arkansas Highway & Transp. Dept.	IGH	11/01/86	1,200,000	1,100,000	1	1685	1	9	9	0	2
California Dept. of Transportation	APL	1/01/84	34,000,000	34,000,000	4	-	-	688	500	1	1
Colorado Dept. of Highways	ATL	10/15/83	1,600,000	2,200,000	1	1824	3	16	65	2	1
Connecticut Dept. of Transportation	IGH	9/25/85	1,069,889	-	1	1670	1	8	5	0	1
Delaware Dept. of Transportation	IGH	7/01/84	800,000	1,000,000	1	1060	1	4	150	1	1
Florida Dept. of Transportation	IGH	1/01/77	300,000	7,000,000	19	19920	20	85	75	2	20
Georgia Dept. of Transportation	IGH	12/01/84	1,200,000	2,000,000	2	3816	4	11	8	3	2
Idaho Transportation Department	IGH	2/01/84	361,000	1,104,000	2	2871	2	9	6	2	5
Illinois Dept. of Transportation	IGH	6/01/82	700,000	10,000,000	50	16535	14	52	20	3	11
Iowa Dept. of Transportation	IGH	12/01/85	1,100,000	2,500,000	2	6386	3	20	10	0	9
Kansas Dept. of Transportation	IGH	7/01/86	1,500,000	1,500,000	1	3140	2	26	4	2	1
Kentucky Transportation Cabinet	IGH	5/01/83	600,000	2,000,000	2	2477	2	16	23	3	1
Louisiana Dept. of Transp. & Dev.	IGH	10/01/83	800,000	1,200,000	1	1396	1	15	7	1	8
Michigan Dept. of Transportation	IGH	1/01/77	600,000	2,500,000	2	6197	4	30	10	5	4
Minnesota Dept. of Transportation	IGH	12/01/79	453,000	5,000,000	4	4800	4	38	18	11	1
Missouri Highway & Transp. Dept.	IBM	1/01/88	2,700,000	1,600,000	3	9070	2	18	4	3	5
Montana Department of Highways	IGH	2/01/86	1,070,000	1,013,000	1	1907	1	8	8	1	4
Nebraska Department of Roads	IGH	4/01/85	1,255,000	174,500	1	2483	1	16	7	1	2
New Hampshire Dept. of Transp.	MDC	1/01/87	1,000,000	1,000,000	1	1368	1	13	2	0	1
New Jersey Dept. of Transportation	IGH	5/01/85	800,000	1,500,000	1	900	1	13	12	0	1
N. M. State Hwy. & Transp. Dept.	DNS	8/01/86	4,700,000	4,000,000	6	1863	6	23	143	4	1
New York State Dept. of Transp.	IGH	11/01/84	2,000,000	5,000,000	17	0	17	60	20	12	2
N.C. DOT Division of Highways	IGH	8/01/86	3,200,000	3,000,000	3	4718	3	28	20	1	12
Oregon Dept. of Transportation	IGH	7/01/84	1,025,000	2,073,900	2	3953	2	9	11	3	10
Pennsylvania Dept. of Transportation	IGH	11/01/83	884,500	5,800,000	16	20865	18	61	47	1	13
South Dakota Dept. of Transportation	IGH	9/01/85	900,000	910,000	1	1350	1	6	4	1	4
Tex. Dept. of Hwys. & Pub. Transp.	IGH	1/01/84	-	16,000,000	43	50476	26	300	156	30	22
Utah Dept. of Transp. - Roadways	TTX	7/01/86	89,000	-	1	70	1	4	0	1	0
Vermont Agency of Transportation	IGH	8/01/83	280,000	800,000	2	2936	2	8	7	1	1
Washington State Dept. of Transp.	IGH	9/01/83	1,200,000	3,000,000	3	2938	7	19	20	1	19
Wis. Div. of Hwys. & Transp. Serv.	IGH	5/01/82	170,000	1,957,000	2	4000	2	14	8	5	13
Wyoming Highway Department	IGH	7/01/85	1,250,000	2,000,000	2	3867	2	23	7	1	4
Alberta Transportation	IGH	12/15/83	1,200,000	2,800,000	1	2745	2	23	8	2	1
Manitoba Dept. of Hwys. & Transp.	IGH	11/01/86	640,000	640,000	1	1011	1	5	5	1	2
Northwest Territories DPW & Hwys.	HPD	1/01/85	100,000	300,000	3	161	0	5	0	2	0
Ontario Ministry of Transportation	ACDS	4/01/86	150,000	300,000	2	240	2	2	2	2	0

[a] ACDS = Autocad; APL = Apollo; ATL = Autotrol; DNS = Diginetics; HPD = Hewlett Packard; IBM = IBM; IGH = Intergraph; MDC = McDonnell Douglas; TTX = Tektronix

it may prefer to receive the consultant's design in a CADD format in addition to the usual hard copy format of blueprints or reproducible drawings.

In the survey conducted for this synthesis, only 3 DOTs out of 39 respondents using CADD indicated that they required consultants to submit their designs in a CADD format. However, 14 other respondents indicated that they *expected* that CADD will become a mandatory format for consultants in the future. The same number of respondents indicated that if a CADD submission were required the consultants would be permitted to provide the CADD files in a "neutral" format rather than in a format of their own CADD system. Several currently available neutral formats are Initial Graphics Exchange Specification (IGES) developed by the National Bureau of Standards, Intergraph Standard Interchange Format (ISIF) developed by the Intergraph Corporation, and Drawing Exchange Format (DXF) developed by Autodesk, Inc.

DATA EXCHANGE AND COMMUNICATION

The data contained in CADD files are quite often useful to a number of organizations outside of the state DOT. Mapping information is particularly useful to federal, other state, and local government agencies. In the past, manually prepared mapping information was of interest to these other organizations. However, a digitized map is a "dynamic" map. It has the capability of being plotted at an infinite number of scales. It also has the ability to combine various themes of information as overlays to produce customized mapping products. This feature of CADD technology has made computer mapping files much more flexible and of much greater benefit to other organizations. Other organizations can use these data to update their own mapping products at a reduced expense. Engineering design information contained in CADD files is also useful to architectural/engineering consulting firms, who can use the information to supplement or coordinate with their own design projects.

Assuming the other organization to whom the data are being provided also owns a CADD system, it is best to exchange the data in a computerized format as opposed to a traditional set of blueprints. In this way, the organization can continue to take advantage of the productivity advantages of the CADD without incurring the expense of creating the CADD data base.

However, there is an important hurdle that must be overcome in order to make the data exchange possible. The data have to be presented in a format that is readable to the receiving organization's CADD system. When both organizations use the same CADD system and both have maintained their CADD operating system at the most recent release level there should be far fewer problems in exchanging data. When one vendor's CADD system differs from another, the data must be rewritten in a format that is readable by both CADD systems. This chapter has presented several of these "neutral formats" supported by the various CADD vendors. Those most commonly used for mapping data are:

- Intergraph Standard Interchange Format (ISIF)
- AutoCAD Drawing Exchange Format (DXF)
- Initial Graphics Exchange Specification (IGES)
- United States Geological Survey Line Graph (DLG)

A majority of respondents to the survey conducted for this synthesis (62 percent) indicated that ISIF was the neutral format used.

PITFALLS IN PRACTICE

The following are areas in which mistakes are often made in applying CADD to engineering, design, and drafting:

- *Purchasing unneeded software*. CADD vendors have developed a wide variety of software programs for user applications. The vendor's sales presentation is designed to very convincingly convey the program's usefulness. Moreover, the software is often related to an application area to which the purchaser very much wants to apply CADD. Nonetheless, often the user finds that purchased software packages are used infrequently or not at all.

Sometimes this is because the program does not meet the purchaser's specific needs for that application area. Or, the purchaser finds that the software would be useful but other application areas are much more productive and cost-effective. Therefore, the application that would use a particular software program is not put on CADD so the program is never used.

Two possible remedies to this problem are (a) carefully planning CADD applications, then purchasing only the software needed to support planned applications and (b) carefully evaluating vendor sales literature and product demonstrations.

- *Skimping on hardware*. Strict budget constraints often force the buyer to scale down a CADD system purchase in an effort to meet budget restrictions. The buyer may have to "live without" items that were recommended or that he or she wanted to include in the procurement. This most often occurs when specifying the CPU capacity or memory and when selecting peripheral devices, including tape drives, disk drives, and plotters. The prevailing attitude is "We can get by without it." Unfortunately, this often leads to frustrated user personnel who are confronted with disk drives that are full, CPUs that are too slow, long plotting turnaround times, and a number of other hindrances to efficient production.
- *Putting inefficient applications on the CADD system.* There are many drafting tasks that require as long to accomplish on the CADD system as they do to accomplish using traditional manual drafting techniques. These are most often "one time" drawings and "one of a kind" drawings that will be drawn once and never required again. These may also be drawings with very little repetition of drawing elements. Or they may be drawings that are needed by only one user and not shared with others. In all of these cases, it may actually cost more to do the work on the CADD system. The production time is comparable to manual drafting yet the production tool is more expensive to use and may create morale problems.
- *Not adequately specifying the format of a consultant's CADD products*. When a consultant is required to use CADD to accomplish design work for a state DOT, it is imperative that he or she be given a specification for CADD standards (i.e., data format, operating system, data density, levels, colors, line weights, line styles, text fonts, standard details, sheet border, etc.) that agree with those of the state DOT. In addition, the data must be presented in a format that is compatible with the DOT's CADD system. When these two requirements are neglected the CADD drawings delivered by the consultant are

of little benefit. The agency must make extensive changes in the consultant's CADD files to make them useful.

If the data are presented in a format different than that of the DOT, a translation must be made. If a "neutral" format is provided, this translation may prove to be fairly accurate. If not, the translation may be only 60 to 90 percent accurate. The data that do not translate will then have to be corrected at a graphics terminal in a very time-consuming and costly process.

CHAPTER FOUR

PERSONNEL

SELECTION AND SOURCES OF CADD TRAINEES

The survey conducted for this synthesis asked state and provincial DOTs what selection criteria had been established when seeking new "workstation operators." The overwhelming majority of responses indicated that existing personnel were the primary source of supply, with only a handful indicating other sources, including community colleges and public announcements. When specific criteria selection were mentioned, these included "high school degree," "3–5 years' experience," and "associate's degree in civil engineering technology." Nonetheless, such specific selection criteria were rarely mentioned.

Other important characteristics of new trainees were "desire," "aptitude," and "productivity." Also mentioned were "willingness to work nights" and "computer training." However, it was very clear that the most preferred choices for new trainees were existing personnel with basic experience in design or drafting functions and an interest in CADD.

A number of respondents indicated an approach to CADD training that is worth noting. They indicated that CADD training was provided to *all* design and drafting personnel. The final selection of personnel to use the CADD system on a full-time basis was based on their performance during this CADD training program. Employees remained in their current assignment pending selection to work on CADD. This approach enables management to evaluate the potential of *all* employees, not just those who show an interest or appear to be good candidates. It also helps reduce the potential for embarrassment to employees. When an employee is selected to work on CADD and, after training, is returned to the former assignment because of an inability to master the CADD process, he or she may be embarrassed to have "failed." By training all employees, everyone is given the opportunity to prove their capability while remaining in their current position. This removes the threat of such embarrassment.

It is also important to note that a number of respondents objected to the term "workstation operators." They indicated that the CADD system was a tool to be used by all personnel. They viewed CADD as being like a pocket calculator. Thus, there were no personnel assigned to work exclusively on the CADD workstation. All personnel, including designers and draftsmen, had access to the CADD system. It was a resource available to all. One DOT employing this philosophy indicated that these personnel generally spent less than half of their time working on the CADD system. On the other hand, another DOT using a centralized or pooled workstation operation indicated that such a system provides ongoing training for their full-time operators.

TRAINING

Computer-aided design and drafting technology represents a significant new learning experience for many drafting personnel. Some engineers may not find CADD technology to be so novel because of their previous work with computers. Nonetheless, the transition to using the CADD system represents a very different way of doing work for both types of employees.

Highly skilled draftsmen rely on refined eye/hand coordination skills as well as their knowledge of the technical content of their drafting work. The CADD workstation operator must still employ technical knowledge and certain eye/hand coordination skills. However, he or she is no longer using the small-muscle motor skills that were formerly used in hand drafting. Similarly, the artistic skill that is the hallmark of a good draftsman is almost unneeded by the CADD operator because the CADD system produces standardized text, line weights, line styles, and patterning with mechanized certainty. Instead, he or she must learn to coordinate hand movements on the command menu tablet with the drawing image displayed on a workstation screen at or above eye level. This is a significant departure from the manual drafting practice of working directly on the drawing with the drafting instrument.

These factors combine to make the draftsman's transition from manual drafting to CADD technology a difficult one. As a result, the "mortality rate" of new CADD trainees can be high. Many employees trained to use a CADD workstation on a full-time basis are not able to make the transition and reach a satisfactory level of production. With this consideration in mind, the survey conducted for this synthesis asked DOTs what the minimal allowed time was in determining whether a new workstation operator was suited for the occupation. Twenty-five responses were received indicating that, on the average, five months were allowed for this evaluation period. The responses ranged from 1 month to 12 months. Most responses (19) were between four and six months.

As mentioned previously, most of the DOTs responding to the survey conducted for this synthesis had purchased CADD systems from the Intergraph Corporation. Intergraph provides basic CADD operator training and CADD system management training as a standard component of the system purchase. Therefore, it was not surprising that all but one respondent indicated that the vendor of their CADD system provided basic workstation operator training. The majority (35 out of 39) also indicated that they have established their own in-house basic training program. Of the four who do not now provide basic training, two indicated that they would do so in the future. However, less than half (17 of 39) indicated that they have established ongoing training for advanced CADD operators.

Finally, the survey found that it takes an average of 4.8 months for a new CADD operator to reach satisfactory production rates. These responses ranged from a low of 2 months to a high of 12 months. Most (33 out of 38) were in the range of two to six months.

PERFORMANCE EVALUATION

The survey asked what criteria are used to evaluate the performance of workstation operators. Out of 29 respondents using CADD and answering the question, 4 reported that no criteria were used. Two of these commented that this was an important problem that needed a resolution.

Those who cited evaluation criteria most often referred to three general factors:

- Productivity, speed, or quantity produced;
- Accuracy or quality of work; and
- Knowledge or understanding of the CADD system.

However, of the 25 responses indicating that performance evaluation criteria were used, only 6 said that *standards* for productivity were developed and applied. The majority wanted speed but apparently had not given employees a quantitative definition of what was expected.

The survey also asked the DOTs what the annual percent turnover among workstation operators was. Thirty responses were given, indicating an average of 16.3 percent turnover in workstation operators per year. Responses ranged from a low of 2 percent to a high of 60 percent. Most responses (24) were between 5 and 30 percent.

The survey asked how pay increases were awarded to personnel using CADD. Not surprisingly, nearly all responses referred to either the state's civil service merit pay system or to union contract agreements.

The survey also asked what production incentives have been used. Out of 33 respondents using CADD, only 3 mentioned incentive programs. They were a cash award program for useful suggestions, an employee recognition program, and a practice of sending the top employee to an annual national users' group meeting.

STAFFING

In the past, the traditional highway-design process has required a mixture of drafting personnel and design personnel. Designers have included both former drafters who design by applying standard formulas and procedures and college graduate engineers. However, designers relied primarily on the drafters to produce finished construction documents.

Computer-aided design and drafting system technology now permits designers to perform their design work directly on the CADD system. Because of its capabilities, designers may use the CADD system both as an aid in computational analysis and as a drafting tool. In the past, time-consuming and complicated coordinate geometry calculations were often assigned to technicians who specialized in that field. Similarly, time-consuming and tedious drafting functions were assigned to trained drafting technicians. However, the CADD system is capable of executing complicated analytical functions for the designer requiring only a relatively small amount of his or her time. Similarly, the designer can perform repetitious and tedious drafting functions using the CADD system and be assured that the graphic quality of the final drafted product will consistently meet or exceed manual drafting standards.

For these reasons, many CADD system users have reduced the ratio of draftsmen to designers. Designers are using the CADD system to do the functions that were formerly assigned to technicians and draftsmen. In the 1988 TRB survey, state DOTs were asked how many workstation operators they employed and, of these, how many are primarily drafters and how many are primarily designers. The percent of draftsmen ranged from 0 to 100. On the average, drafters accounted for 75 percent among 37 responses. More than a third (14 out of 37) said 100 percent of their workstation operators were drafters. Only one said all of the workstation operators were designers.

COMPENSATION

Compensation for personnel using CADD is another important issue. These personnel receive a great deal of training and represent a significant investment. Moreover, they are potentially several times more productive than their counterparts doing manual drafting. Therefore, retaining qualified personnel capable of using the CADD system is very important.

The survey asked what the standard starting hourly pay rate for workstation operators was. Twenty-three responses were received. These responses ranged from a low of $6.00 per hour to a high of $13.50 per hour. The average hourly starting rate was $8.30. Almost three-quarters of the responses (17 of 23) fell in the range of $6.33 per hour to $9.40 per hour.

The questionnaire also asked for the maximum hourly pay rate. Twenty-four answers were received, ranging from a low of $10.00 per hour to a high of $25.00 per hour. The average maximum pay rate was $14.54 per hour. Three-quarters (18 of 24) fell in the range of $12.21 per hour to $17.32 per hour.

SHIFT WORK

The CADD system is a significant capital investment. Therefore, there is a need to use the system as much as possible. Managers are reluctant to allow such an expensive resource to sit idle. It has also been shown how a multiple-shift operation can reduce the hourly operating cost of using the CADD system. Moreover, there often is not enough equipment available to satisfy everyone's desire to use it. This unsatisfied demand can be another reason for operating more than one shift on a CADD system per day.

Sixty-two percent of the survey's responses (24 out of 39) indicated that they operated their CADD system more than one shift per day. Nineteen respondents said they operated two shifts per day and five respondents said they operated three shifts per day.

The DOTs were also asked by the survey if they offered a pay differential for shift work. Fourteen of 25 (56 percent) said that they did. The average hourly differential was $0.56 per hour. These pay differentials ranged from $0.25 to $1.19 per hour.

Several CADD managers reported that it is very difficult to transfer employees to an evening or night shift. For this reason, their DOTs find it necessary to hire employees from the outside for these shifts. These employees know that they are being hired for shift work and are more agreeable to it.

UNIONS

Many state DOTs employ union personnel in technical disciplines including drafting and mapping. The survey asked if CADD workstation operators were unionized. Sixty percent (21 out of 35 responses) said yes.

ORGANIZATIONAL STRUCTURE

The CADD system is both a computer system and a technical tool used for design and drafting work. As such, an interdisciplinary team of personnel is required to make it successful. These team members include draftsmen, designers, managers, computer programmers, and computer system operators. Even with PC CADD the user quite often needs assistance from data-processing specialists in order to work effectively.

The question "Is the CADD system a computer system or a design tool?" then arises. If the CADD system is viewed as primarily a computer system, it might be logical to place control of the entire CADD system in the hands of the data-processing staff, with only workstations available to the users. If it is viewed as strictly a design tool, then it might be logical to place it entirely in the hands of the technical department using it.

The 1984 TRB survey (*1*) found that more than half (56.4 percent) of the state and provincial DOTs assigned management responsibility for the operation of the computers to the computer/automation and information systems group. The remainder assigned this responsibility to technical user areas. At the same time, management responsibility for the operation of CADD workstations connected to the computers was assigned to the computer/automation department less than 3 percent of the time. The vast majority of the DOTs assigned this responsibility to user departments including design, mapping, photogrammetry, drafting, etc.

OTHER ISSUES

DOTs responding to the survey conducted for this synthesis indicated that on the average, 83 sq ft were allocated to a CADD workstation. The majority (30 out of 36) ranged between 60 and 100 sq ft. All responses indicated that a workstation operator dress code had not been established.

PITFALLS IN PERSONNEL ISSUES

In preparing this synthesis, the following errors were identified as being most critical and the most often committed during the process of personnel management on the CADD system:

- *Failing to provide adequate training.* CADD system capabilities are extensive. Most CADD system and computer commands are not difficult to learn. However, it is difficult to master all of the hundreds of CADD system software and computer operating system commands available to the user. Moreover, training and experience are required to learn the proper combination of commands that achieve the best result using the least effort. This skill must be emphasized. Most drafting and design functions can be performed using a number of different approaches. However, one approach will often take considerably less time than the others. Computer-aided design and drafting system users who are not acquainted with all commands that are available or the best approach to take to execute a given function are working below their potential.

Most CADD operators can, given enough time, learn all CADD system commands and, through trial and error, master the best approach to a given task. However, as discussed above, it can require several months for CADD users to become fully proficient on the system. Meanwhile, a CADD system user operating below potential capacity has cost the organization thousands of dollars in lost productivity while advancing on the "learning curve." Users will often employ basic commands and processes that are relatively inefficient for long periods of time simply because they are not aware that more efficient commands and processes are available. Or they may be aware that more efficient commands are available but refuse to take time out from the task at hand to ask about or research new commands. This is despite the fact that the effort required to master them would be recovered many times over in the future.

Proper initial training by qualified instructors in a structured training program, ongoing training, and continuing user support will eliminate much of this inefficiency and significantly shorten the learning process. Moreover, the training should include system support personnel and supervisors with responsibility for CADD usage.

- *Giving employees with unacceptable performance levels too long to improve.* The initial training program to get a new CADD user started is a significant expense. Therefore, managers want to capitalize on that expense and give new users ample time to master the system. However, sometimes the new user fails to demonstrate consistent progress in mastering the CADD system. This lack of progress may last for several months without any significant signs of improvement. Managers tend to be patient and hopeful during this period because of their desire to recover their training investment and their reluctance to confront employees with their failure to master the system. Nonetheless, when this process occurs over several months with no sign of improvement, the manager is simply wasting money.

Instead, the manager needs documented standards of productivity on selected tasks that can be used to make an informed and objective evaluation of the new user's progress and potential for success. The manager also needs to recognize that new users trained from the start on the CADD system will not master the technology around half the time and must be willing to make changes as needed.

- *Failure to maintain adequate pay scales.* As the number of CADD workstations deployed in the engineering industry has grown so has the demand for qualified technical and design personnel to operate them. Computer-aided design and drafting workstations have been sold by vendors at a much faster pace than people have been trained in CADD. This has resulted in a growing unsatisfied demand for trained and experienced CADD operators and increased CADD operator salary levels. Consequently, CADD operators have had ample opportunity to achieve higher salary levels by joining other organizations. Salary levels have increased so fast that many organizations have fallen significantly behind in the industry. This leads to a significant turnover problem as CADD operators take advantage of higher salary offers to make job changes. In view of the expense of training a new CADD operator and the tremendous potential for productivity increases that this represents, turnover among CADD operators is a major concern. Organizations that fail to keep their pay rates in line with the industry norms may have a difficult time keeping qualified CADD operators.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This synthesis has shown that many state DOTs use CADD for highway design. Departments of transportation have made major investments in money, labor, and organizational energy to implement CADD technology. About half of the design drafting work accomplished at DOTs using CADD is being done on those systems. Moreover, DOTs indicate that CADD has given those using CADD substantial productivity increases over manual design and drafting procedures. These productivity increases have been more than sufficient to offset the operating costs of the CADD systems. Thus, there has been a net savings in the cost of drafting design functions as a result of using CADD.

CADD is being used in a variety of application areas, but primarily in mapping, automated survey data collection, roadway design and drafting, bridge design and drafting, and photogrammetry. Moreover, new software application programs are being developed by vendors and by the DOTs themselves. It appears feasible that the entire mapping, design, and drafting process can and will be automated using CADD systems.

On the other hand, the road to successful CADD usage appears to have some serious drawbacks. Chief among these is obtaining top-level management support for the program. Another key issue is providing sufficient ongoing training, development, and user support to facilitate the growth of the CADD program within the DOT. Departments of transportation must also carefully examine personnel policies for CADD users, especially compensation packages, in order to maintain a well-qualified and experienced staff in the face of tremendous market demands for these employees by other industries.

RECOMMENDATIONS

The following checklist is recommended as a guide to the selection, implementation, and management of CADD systems:

- Obtain committed support from top-level managers;
- Conduct a requirements analysis;
- Employ a systematic selection process to evaluate all vendors;
- Develop a comprehensive implementation plan;
- Identify all purchase costs;
- Identify all operating costs;
- Establish an ongoing user support and training program;
- Carefully examine and plan all applications for the system before its purchase;
- Set productivity improvement guidelines;
- Set data standards;
- Establish personnel policies for CADD users. These policies should cover the following issues:
  - Personnel selection
  - Performance evaluation
  - Compensation
  - Shift pay
  - Promotion
  - Discipline

It appears that computer systems will continue to show dramatic reductions in hardware costs coupled with dramatic increases in system capabilities. These increases will be seen in CPU processing speed, storage device capacities, display system capabilities, input devices, and output devices. There appears to be a strong trend toward engineering workstations and the UNIX operating system.

This synthesis has purposely not focused on technology but instead on management application and personnel issues. It is the final conclusion of this synthesis that these principles apply equally well to these new developments. The fundamentals of system selection, implementation, and management must be practiced regardless of the progress that is seen in CADD technology.

REFERENCES

1. Rioux, T.W., "Use of Interactive Graphics at State DOTs," unpublished surveys conducted for the Transportation Research Board's Committee on Computer Graphics and Interactive Computing.
2. "1988 CADD Application and User Survey," *PSMJ* (July 1988) pp. 17–24.
3. *IGRDS Brochure*, American Association of State Highway and Transportation Officials, Washington, D.C. (1987).
4. Campbell, J., "Bridge software saves a bundle," *ENR* (December 3, 1987) p. 20.
5. "Bridge Designer," Micro Systems Solutions, Inc. (1988).

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

TRANSPORTATION RESEARCH BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED