CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Construction Site Applications of CAD

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CONSTRUCTION SITE APPLICATIONS OF CAD

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Executive Summary

Despite the industry's slow progress toward integrating the entire design and construction process, computer-aided design tools (CAD) have evolved to a point where they can support field engineering and construction operations apart from a totally integrated environment. Most field engineering functions rely on graphical presentation to communicate the engineer's intent. CAD gives the constructor access to vast amounts of new design data and assists in effective technical communication with the field. Constructors who use CAD will be able to improve their field engineering activities; constructors who innovate with CAD will develop new construction aids that will significantly improve their overall construction operations and gain a competitive advantage over their non-automated competitors. These benefits are available to constructors now.

This report discusses results from an in-depth investigation of CAD applications in construction. The researchers interviewed key people at nine construction firms, two large engineer, procurement and construction (EPC) firms and seven construction-only firms, and surveyed approximately 750 US and Japanese construction companies to determine how they use computers and CAD. By studying how each of these company implemented and used CAD, the researchers found numerous innovative applications of CAD in construction. Further, they identified capabilities of CAD that support construction, characteristics of successful implementation of CAD and barriers to increased use of CAD in construction.

Although very limited, the background literature concerning CAD and its applications in construction leads to the following conclusions:

- Technology is not a problem in allowing construction firms access to electronic design information. The technology exists, its costs have become reasonable and it can be configured in a variety of ways to support construction.
- Design firms have blazed the path in implementing technology in the architecture, engineering and construction (AEC) industry and construction firms can learn from their experiences.
- CAD use in the design phase of a project is increasing and therefore electronic design information is increasingly available to the constructor. The transfer of data to the constructor, though, is not yet automatic.
- Several large EPC firms have developed and implemented integrated project design and management systems that allow their construction forces to access the electronic design data. The background literature does not indicate whether

or not these firms use workstations on construction sites to explore possible uses beyond those envisioned by the system developers.

- The literature offers only slight speculation of the value of electronic design information to construction forces and provides no examples of constructors using of CAD on the construction site.

Pre-Construction Applications of CAD

Large EPC firms use 3D electronic models of facilities, which their engineers and designers develop, to plan construction before they move people to the site. Internal integration allows the construction forces of these companies to view the complete design model early in the process rather than merely receiving standard plans when the design is complete. Access to the 3D electronic model allows these firms to plan and simulate construction operations.

3D modeling systems specifically support construction operations by allowing:

- 3D visualization of different perspectives;
- dynamic simulation of construction operations;
- batch materials take offs for accurate materials quantities.

Applications of CAD During Construction

2D CAD can be used to effectively support construction now. 2D CAD supports and enhances the constructor's execution of a variety of field engineering tasks. Most construction companies begin using CAD to produce standard construction drawings. Those with innovative operators soon learn that 2D CAD enables them to perform standard operations better and to create new, beneficial construction information. The constructor's ability to take advantage of this new power is limited only by the needs of their project and the imagination and skills of their users.

Table 1 lists many ways constructors currently use 2D CAD to improve their field engineering activities:

TABLE 1: Applications of CAD During Construction

Automating Old Processes		New Processes and Products
Concrete Lift Drawings	*	3D Viewing
Formwork Drawings	*	Scaled Overlays
Concrete Placement Drawings	*	Borrow Pit Model
Precast Concrete Operations	*	Rock Bolt Analysis
Isometric Drawings		Equipment Adequacy and Access Analysis
Fabrication Drawings		Up-to-date Information
Layout Drawings		Claims Quantification
Shoring Drawings	*	Stockpile Management
Traffic Flow Diagrams		Plot in Appropriate Format
Scaffold Design and Layout Drawings		Integrated Materials Management
Construction Sequence Drawings		
Bridge Falsework Designs	*	
Survey Control Plans	*	
Modifications to Design Drawings		
Subcontractor Coordination	*	
Drawing Logic Networks		
Utilities Mapping		

(* indicates that CAD added capabilities in excess of just supporting drafting operations.)

Constructors can exploit several important capabilities of 2D CAD systems to support their construction operations. These include:

- the ability to **copy and reuse drawings** to make their design and drafting efforts more efficient, more consistent and less error prone;
- the ability to **make changes easily** to accommodate design modifications and additions, to correct design errors, to accommodate as-built conditions and to insure that field crews have accurate and current information;
- the ability to present design information **clearly and consistently** to avoid misinterpretations and confusion in the field;
- the ability to **layer design information** for efficient viewing and plotting;
- the ability to represent objects at **full size** to establish accurate spatial relationships between objects and assist in **detecting interferences** between objects;
- the ability to **plot complex shapes and give accurate dimensions** for construction layout;
- the ability to **plot drawings in most appropriate format** ranging from standard drawings sizes to 8.5"x11" sheets;
- the ability to **access automatically generated geometric information** about objects to bridge the gap between drafting and design;
- the ability to **customize the system** to support routine or complex operations;

- the ability to **market the company** as a technically advanced constructor;
- **improving overall communication** of construction information.

Constructors who understand these capabilities of CAD will find new and innovative ways to approach field engineering activities.

Currently, general contractors make only minimal use of 3D models to ease visualization of complex areas or structures. Despite strong incentives, cost, time and complexity prevent most constructors from using 3D models extensively at construction sites.

Conclusions Regarding Successful Implementation of CAD in Construction

Companies that currently use CAD effectively in their construction operations share several characteristics:

- They rely primarily on engineers to operate their systems rather than former drafters.
- They use relatively advanced computers and peripherals (386 based computers and electrostatic plotters).
- They take advantage of advanced capabilities of their CAD systems to leverage their efforts.
- They are committed to using CAD because they understand its capabilities and how those capabilities can support their construction operations.
- They focus on construction/field engineering tasks whether performed in the field or in the home office and do not get distracted with other non-construction oriented applications.

Conclusions Regarding Barriers to Use of CAD in Construction

Technology is not a barrier to the use CAD in construction. Current technology can be used effectively to support field engineering and construction. The primary obstacles lay in the organizational characteristics of specific companies (organizational barriers) and the general nature of the construction industry (institutional barriers).

Organizational barriers include:

- a lack of people trained to use CAD;
- a lack of appropriate internal and external training programs for available personnel;
- too little time for operators to experiment and learn advanced capabilities of CAD systems;

- a lack of champions committed to making CAD succeed on construction sites;
- a lack of corporate plans that consider CAD as an important tool;
- a lack of experience by project managers and engineers to manage and exploit this new and unfamiliar tool;
- reluctance to accept expensive CAD systems in overhead;
- inadequate hardware to run the software and produce output efficiently;
- insufficient systems administration efforts to establish procedures, maintain hardware, train people and customize systems;

Institutional barriers include:

- industry fragmentation;
- a lack of owner involvement;
- designers not using CAD universally or completely;
- a different working environment for CAD operators;
- a general lack of consideration about using CAD in construction;
- research focused on design integration with little consideration of how constructors fit in an integrated project environment or benefit from CAD.

Recommendations

The researchers offer the following recommendations in four general phases of CAD implementation to assist construction companies that are considering using CAD in construction operations:

Planning

- Understand CAD, both what it can and cannot do.
- Cultivate champions; champions make things work.

Getting Started

- Buy appropriate systems; don't try to save money on hardware.
- Train engineers, to eliminate the middle man and foster innovation.
- Train managers to understand how CAD can support them.
- Establish CAD operating procedures.
- Administer the system to insure it works efficiently.
- Identify good starting activities, early success breeds confidence.

Progressing

- Explore advanced capabilities of CAD to leverage design efforts.
- Balance CAD workload between project site and home office.
- Evaluate progress to focus on productive applications.

- Disseminate lessons learned to encourage increased use of CAD.
- Stay informed about technology by reading current publications and attending trade shows.

Interfacing with External Organizations

- Request electronic data transfer, integration offers great advantages.
- Participate with universities to teach engineers CAD.

Recommendations for Future Research

The researchers identified several areas that require further investigation. These include:

- determining how layering standards should support construction;
- determining how general contractors can best share design data with subcontractors electronically;
- continuing to focus on barriers to project integration;
- developing university curricula to teach engineers CAD;
- analyzing field engineering to explore other activities that CAD could improve.

Reader's Guide

The main body of this report is divided into three chapters. Chapter 2 discusses the background literature. Chapter 3 describes actual applications of CAD in construction and highlights the capabilities of CAD that support construction site use. Chapter 4 shows how the companies studied implemented CAD and identifies characteristics of success and barriers to implementing CAD in construction. Chapter 5 highlights conclusions, recommendations for practice and needs for future research.

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CHAPTER 1

THE PROBLEM AND POTENTIAL FOR USE OF CAD IN CONSTRUCTION

The Problem

Construction researchers have focused on integrating construction project execution from design, through construction, to facility management using computer-aided design (CAD) tools, related databases and artificial intelligence/expert systems. There has been little attention, however, to identifying how constructors will benefit in an integrated construction environment or how they can benefit using currently available CAD tools. This report will help fill this void.

The Potential

While researchers and practitioners strive to integrate the construction process, much of the construction industry remains isolated from possible improvements using available technology. Large internally integrated design/construct firms continue to develop and implement advanced modeling systems that allow them to construct facilities electronically before work begins in the field. These firms can develop designs in detail, plan and simulate construction operations and ultimately turnover a complete electronic model of the constructed facility to the owner for later use managing the facility. Unfortunately, the majority of the construction industry cannot participate in this grand vision of an integrated construction environment. Many barriers internal to individual companies and inherent in the construction industry prevent the integration of design and construction functions; often there is no integration of the design process so their is no monolithic design to transfer to the construction phase, which itself is highly fragmented. Despite the industry's slow progress toward integrating the entire design and construction process, CAD has evolved to a point that allows it to support construction operations apart from an integrated environment.

CAD means many things to many people. To some, computer-aided drafting is an electronic improvement of the drafting process, which itself remains relatively unchanged. To others, computer-aided design implies that the computer assists the designer in accomplishing his responsibilities. CAD really accomplishes both of these functions. It can improve the appearance of anyone's drafting and it supports all but the most advanced designers. Further, CAD can operate in only two dimensions, or it can model entire facilities in three dimensions. Constructors can take advantage of both 2D and 3D CAD systems in their field engineering.

The process of drafting with CAD generates a tremendous amount of data associated with the objects the user draws. For example, the end points of a simple line are specifically located in the drawing plane, so geometric coordinates are automatically associated with those endpoints. In addition to vast amounts of new data, CAD is a powerful computational device that allows the user to manipulate that new data to create useful information. To further the example, if the endpoint of a line represents the end of a wall, CAD can easily calculate where the wall is in relation to any other object in the drawing. Constructors can significantly improve their construction operations if they understand what sorts of data their CAD systems generate and how they can manipulate that data to create information useful to their construction forces.

Contractors do a considerable amount of design work in preparing construction drawings to support their crews. They design formwork and prepare lift drawings for concrete placements; they prepare isometric, and in some cases, fabrication drawings for pipe and steel sections; they prepare shoring and falsework plans; they use site layout and traffic control drawings; they detail construction operations using sequence drawings; they coordinate the information supplied to subcontractors; and they perform many more activities that fall under the umbrella of "field engineering." Most of these field engineering functions rely on graphical presentation to communicate the engineer's intent. CAD can assist the contractor in preparing the necessary drawings and at the same time give the contractor access to vast amounts of new design data.

These benefits are available to constructors now. Current design practices and tools can generate new information that is valuable to the constructors. Constructors who use CAD can improve their field engineering activities; constructors who innovate with CAD can develop new construction aids that will significantly improve their overall construction operations and gain an advantage over their non-automated competitors.

The Research

The Center for Facility Engineering (CIFE) at Stanford University sponsored this research project to explore the potential use of CAD during the construction phase of a project. CIFE is a partnership between university researchers and industry members dedicated to advancing technologies to integrate and automate each phase of a facility's life cycle. Two research assistants guided by a faculty advisor from the Department of Civil Engineering established the objectives and followed the research methodology outlined below.

Research Objectives

Four objectives guided the research:

First, the researchers sought to determine the extent to which selected construction companies currently use CAD systems to enhance field engineering functions and support their construction operations. The researchers planned to review current applications of CAD in construction to describe the resulting benefits so that other companies can better understand how CAD could improve their construction operations.

Second, the researchers sought to identify capabilities of CAD that construction companies can exploit using CAD on the project site. The researchers planned to explain the important features of CAD in a construction context to help constructors understand how they can use CAD to improve their construction operations.

Related to the second objective, the researchers sought to identify enhancements to existing systems that would increase job site use of CAD. This will help software developers focus their efforts to support construction applications.

Finally, the researchers sought to describe potential organizational, technical and institutional barriers that prevent or impede the implementation CAD at the construction site and suggest strategies to overcome these difficulties. Each company has to determine its own way to introduce and use CAD. By documenting the experiences of other firms, the researchers hoped to help companies make a more thoughtful analyses of the potential benefits that CAD offers for their operations and the problems that may arise during its implementation.

Research Method

The research involved in two phases: data collection and data analysis. The data collection phase included examining the current literature to identify relevant background and conducting interviews in companies that use CAD in their construction operations. The data analysis phase required the researchers to distill the findings of the interview process to find applications of CAD that improve construction operations and isolate characteristics of companies, projects and individuals that make using CAD in construction successful.

Additionally, the researchers surveyed construction companies in the US and Japan in order to get a better perspective of how construction companies use CAD.

Data Collection

Before interviewing any companies, the researchers reviewed current literature to determine how CAD is reportedly used in the construction industry and identify similar research. The researchers found many articles discussing CAD in the construction industry but discovered no specific investigations of CAD applications in construction. The background literature is discussed in Chapter 2.

Because of the lack of published information concerning uses of CAD on construction sites, this research has been exploratory. The researchers felt that it was necessary to determine if and how construction companies currently use CAD by investigating as many different types of companies and applications as possible within the scope of the project.

The research focused on construction phase operations. The researchers loosely defined this phase as consisting of activities that people responsible for construction do with the design data. Obviously there was room for overlap between design and construction in this definition, but where overlap occurred, such as in the large integrated engineering, procurement and construction (EPC) companies, only the activities that improved construction site operations were discussed. This restriction allowed the researchers to consider CAD use on project sites and in home offices as long as it directly supported construction.

Except for the background literature review, the data collection phase was interview based. The researchers found and focused on nine companies that use CAD to support their construction efforts, seven construction-only contractors and two large engineering, procurement and construction (EPC) firms. While the resulting sample of CAD use is too small to be statistically significant, it does show how companies in different parts of the construction industry have begun to use CAD. It also highlights the benefits and problems that different types of construction firms have experienced in using CAD.

The researchers interviewed over 40 key individuals at these companies to establish how and why they decided to use CAD. The interviews highlight the benefits and problems that different types of construction firms have experienced in using CAD. Reports of the interviews from the seven construction-only companies are included in Appendices A through H; an interview guide for those interviews is included in Appendix K. Additionally, speakers at the Integrated Construction Association's "Integrating the Construction Process" concurrent conference during the AEC Systems Show '90 discussed current work they are doing to take advantage of CAD in their construction. A report of their discussion is included in Appendix I.

Data Analysis

The researchers analyzed the data in four steps:

Consolidation of Interviews

All of the interviews for each company were consolidated into individual company case studies to gain a balanced perspective of how they benefited from CAD and what difficulties they had implementing it. These consolidated case studies laid the basis for further analysis of specific applications of CAD and implementation strategies.

Analysis of Applications

From the consolidated company case studies, the researchers extracted specific applications for detailed description and further analysis. This included identifying the capabilities of CAD made them possible and efficient to help constructors understand how CAD can improve their construction operations.

Analysis of Implementation

Next, the researchers used the data from all of the firms to determine characteristics of successful implementation of CAD and barriers to increased use of CAD in construction. The construction industry is unique, so while construction companies can learn from companies in other industries have implemented CAD, it is particularly important to learn from construction companies how CAD can be implemented and used in the construction environment.

Development of Findings, Conclusions and Recommendations

Finally, the researchers considered both the applications and specific implementation strategies from each company to develop general findings on the current use of CAD in construction. These findings were further analyzed to highlight general conclusions from the research. The final step was highlighting recommendations for future implementation and application of CAD in construction, based on both analysis of the conclusions and suggestions of the people interviewed. The researchers also identified needs for future research.

Survey Methodology

The researchers intended to learn from the survey how companies use CAD, how they think it could be used, what problems they have faced in implementing CAD or what problems have prevented their use of CAD. The researchers conducted the survey in two phases. The data collection phase involved developing, distributing and receiving the survey questionnaires. The analysis phase involved synthesizing the data to find trends and specific applications of CAD. A complete report of the results of the survey is included in Appendix K.

Collection

The researchers developed a questionnaire based on a review of current literature concerning CAD use in construction and and initial interviews with construction firms using CAD. The questionnaire first asks about computer and CAD use and then it focuses on barriers to implementing CAD. Essentially the same questionnaire was distributed to both US and Japanese companies. A few improvements were made to the questionnaire for Japanese companies based on early input received from US participants.

The survey participants were not selected statistically or scientifically. The researchers arbitrarily selected construction companies with annual revenues over $100 million on the assumption that these companies could afford CAD if they saw any value in it..Survey Questionnaires were mailed to 380 U.S. construction firms and 365 Japanese construction firms. The U.S. firms were selected from the ENR Directory of Contractors. The Japanese companies were selected from a similar reference ranking Japanese contractors annually. All questionnaires to each company were mailed concurrently but the responses returned over several months. After the rate of return of fell significantly, the analysis phase began.

Analysis

The analysis phase involved several activities. First, the researchers consolidated the response data in a spreadsheet. Then, the data was exported to a simple database for initial analysis. The results of the initial data analysis were then graphed using a graphing program. Finally, the researchers reviewed the results to assess pertinent findings. This process was iterative because several analyses suggested new ways to review the data so the researchers returned to the data to make new analyses. The graphs of answers to the survey questions and the conclusions that the researchers draw from those findings follow this narrative. The responses were analyzed by size, type of company as appropriate. In several cases, the researchers analyzed the responses to questions based on whether or not the respondent indicated that they used CAD.

A Reader's Guide

The remainder of this report is divided into four chapters to allow the reader easy access to sections of particular interest. The contents of these chapters are as follows:

Chapter 2: Integration, CAD and Construction: the Background: This chapter discusses the findings of a review of current literature concerning CAD and its application during the construction phase of projects. The findings include the benefits of project integration, the state of the art of today's engineering workstation environment, results from several recent surveys of CAD use, examples of companies that currently support construction with CAD systems, discussion of possible barriers to CAD use in construction, and suggestions regarding possible but untried construction site applications.

Chapter 3: Applications of CAD in Construction: This chapter describes over forty different examples of how construction companies currently use CAD to support pre-construction and construction operations, and identifies particular capabilities of the CAD systems that supported construction. The hurried reader may want to browse this chapter and read only about applications of particular interest.

Chapter 4: Characteristics of Success and Barriers to CAD in Construction: This chapter discusses the common threads of successful CAD implementation on the projects studied and the particular problems that the companies encountered in their attempts to use CAD to support their construction efforts. This chapter also presents a framework for comparing the costs and benefits of using CAD to support construction.

Chapter 5: Conclusions and Recommendations: This chapter summarizes the general findings of the research and develops conclusions about the potential for increased use of CAD to support construction. It also makes recommendations to assist companies that wish to implement CAD in their construction operations. Finally, the researchers assess how well the researchers accomplished the research objectives and suggest areas for future research.

Appendices A through L include consolidated findings from the interviews at the seven construction-only companies, a brief report of discussion presented at the Integrated Construction Association portion of the AEC Systems '90 Conference, a copy of the interview guide that structured the research interviews, a complete report of survey results and a bibliography.

CHAPTER 2

INTEGRATION, CAD AND CONSTRUCTION: THE BACKGROUND

Before beginning any new investigation, it was important to understand the state of CAD technology and how it is used throughout the Architecture, Engineering and Construction (AEC) industry. Armed with this understanding, the researchers will be able to focus on new and innovative applications of CAD that support and improve construction operations.

In general, the literature shows increasing interest in total project integration, discusses the technology in depth, surveys current uses of CAD systems and highlights attempts by several large, advanced companies to integrate their design and construction operations. This chapter discusses each of these areas. The literature does not discuss actual construction site applications of CAD.

Integration

The possibility of using CAD to support construction exists largely because of attempts by many forces within the AEC industry to integrate projects from conceptual design to facilities management. Construction is an important step in this process and therefore should be considered as the projects are integrated.

Definition

The Construction Industry Institute, a construction research organization at the University of Texas at Austin, offers the following definition of integration within the construction industry:

> Integration provides a common database that is accessed, used and updated by multiple applications or users. The information in an integrated system is organized in a logical way and demonstrates a centralized behavior with consistent and non-redundant data (Ibbs 1989).

This definition suggests data can be distributed in different databases as long as it behaves in a centralized fashion (Teicholz 1989a). Integration, therefore, does not imply single massive systems, rather it allows for modular systems in which each module communicates and contributes to the total project database. A modular approach in turn means that modules can be developed to support the specific needs of different participants, such as the architect, the engineer or the constructor, without burdening others with unnecessary requirements. A modular approach also implies that early modules can be implemented as they are developed without regard to later modules, i.e. design modules do not depend on facilities management modules, although the reverse is not true.

Integration in the AEC Industry

The AEC industry could benefit significantly from the use of integrated design systems to change and improve the way facilities are designed and constructed (Howard et al 1989). Computer systems could integrate graphical and non-graphical design data with expert systems to improve the quality and consistency of designs and create a platform for improving and automating construction processes and managing facilities. Integrated designs could reduce construction times, reduce design errors and omissions, reduce or eliminate field rework and allow construction automation. While this view of an integrated construction environment considers how constructors would benefit from integration, it does not discuss how they can further exploit the integrated flow of design information.

ICA

The literature introduced the researchers to the Integrated Construction Association, an organization of construction industry professionals who share the belief that all project participants will benefit from the integration of architecture, engineering, construction and facility management using computer-aided design tools (ENR 1989). Leaders of this new organization believe that the technology to affect such integration is available today and that firms just need to take advantage of it. Further, their founder, a construction scheduler, offers a view of total project integration in which constructors enjoy substantial benefits. While he does not elaborate on actual construction site applications as opposed to more general benefits, he does maintain that the constructor will be one of the winners in the integrated environment (Stowe 1989).

Technology

Any attempt to summarize hardware and software developments in CAD systems is both an overwhelming and trivial exercise; overwhelming in the shear volume of information available and trivial because many of the systems are becoming indistinguishable from each other. This researchers sought only to identify the minimal requirements for an efficient CAD system. CAD systems consist of both the software and appropriate hardware. The researchers found an important difference between the minimal functional requirements for a CAD system and the appropriate hardware requirements to operate the software productively.

Hardware

Generally, CAD software must run on advanced computers commonly referred to as engineering workstations. While scores of vendors develop new workstations, the characteristics of appropriate computers for CAD software seems to be converging on a few standards (Bowerman and Fertig 1988, Teicholz 1989).

First, most workstations operate primarily in a stand-alone mode. While workstations are normally networked for access to shared data and access to peripheral devices and general communication, the primary computing power remains with the workstation. Database information is accessed through a server on the network. Early minicomputer or mainframe computer based CAD systems offered terminal and host configurations and the systems operated in a time-sharing fashion. Today's interactive CAD software does not function well in this environment. Not only are these systems extremely expensive, they slow down as more terminals are added to the host. Users add more terminals to improve productivity but generally reduce their productivity by slowing the entire system. Research indicates that response times above 4 seconds seriously degrade productivity (Bowerman and Fertig 1988).

Workstations generally employ 32 bit processors. Some CAD software runs satisfactorily on 16 bit processors but any less 16 bits results in seriously degraded performance. 32 bit processors provide the speed necessary for the intensive computations the CAD software requires. Optimally configured Intel 80386-based workstations may also have additional math and/or graphics co-processor chips and variable storage devices while newer technologies (Intel 80486, RISC) integrate these functions into the chip architecture.

Workstations have large, high resolution color monitors. These are necessary to replicate the detail of skilled drafters and provide the resolution necessary for displaying complex solid images and simply to view entire designs at suitable scales.

Different hardware vendors provide these features in different configurations but the basics remain constant. Workstations with these general characteristics are currently available for between $15,000 and $25,000.

Software

Software evolves to take advantage of improvements in hardware. In addition to basic improvements in the basic CAD software, third party applications come to market almost daily. Despite the large variety of CAD tools available, a few systems dominate the AEC market. Without considering particular CAD packages, several characteristics distinguish CAD systems (Bowerman and Fertig 1988).

Two dimensional CAD systems are generally referred to as electronic drafting boards. While the analogy to a drafting board underestimates the information and power available from 2D CAD systems, they do limit the user to thinking and designing on a single plane.

Many systems have expanded their capabilities to allow the user to design on a series of parallel planes to imitate 3D space, these systems are commonly called 2.5D CAD. While such systems can produce pictures that appear three dimensional, the CAD system does not maintain information about the nature of the components. For many applications this is a useful tool but it falls short of full element modeling.

3D modeling is accomplished using either surface modeling or solid modeling techniques. Surface modeling defines an object in terms of its surfaces, useful for imaging but limited in fully establishing component characteristics. Solid modeling systems define solid elements for which the system can fully define geometric and material characteristics. This is ultimately where CAD systems need to go to become fully useful.

Each level of this hierarchy of CAD systems, from 2D to 2.5D to 3D, offers improved capabilities generally at the cost of increased complexity. While advanced designers use solid modeling CAD systems, most designers just use basic 2D CAD systems that offer accuracy, computational power and consistency that can improve any drafting or design effort.

Workstations generally use advanced operating systems, primarily UNIX based systems. CAD software needs the memory access and filing systems that such operating systems offer. Additionally, many RISC based workstations require such an operating system. Some systems still operate in a DOS or Mac OS environment but in many cases their performance is slower and less flexible.

Integrated Systems

Current technology allows a variety configurations for integrated systems. Options range from single user, stand alone computers maintaining information on different parts of a design in different files to the same system integrating its operations internally using a common design database. More advance systems have multiple workstations networked together sharing information that resides in a common file server and may even have links to remote locations (Teicholz 1989). The technology therefore exists to include the construction site in the integration scheme; the construction site can receive design files on disk or it can be a node on a wide area network. In either case, there are no technical impediments to bringing CAD and integrated systems to the construction site although the literature offers no examples of companies that have integrated their operations to this extent.

Current Use Surveys

Two surveys discuss how CAD is currently used within the AEC industry. One of these surveys focuses on CAD use in general while the second concerns only application of CAD in design firms; both are important to this research. It is useful to know how firms in the AEC industry use CAD, and it is also important to know how design firms are using it so that contractors can know what information is available from the design process.

CAD/CAM, CAE Users 1990: Current Applications and Future Directions

The CAD Report surveyed a random cross section of several industries that use CAD, including manufacturing, construction, utilities and government (CAD Report 1990). The survey considered applications in mechanical engineering, architectural and facilities management, engineering analysis, electrical engineering and computer aided manufacturing. Of particular interest to this research are the findings in the areas of mechanical engineering and architectural and facilities management. The report shows that over 80% of the respondents use CAD for drafting while less than half use it for building design and layout. Further, the survey found that while a variety of CAD systems are available, three systems, AutoCAD, Intergraph and IBM CADAM dominate the architectural and facilities management market today.

These results are significant to this research for two reasons. First, the fact that most CAD use is still focused on drafting indicates that the CAD databases do not include additional design information that would enhance the integration process and assist the constructor. Second, the fact that the market seems to be settling on a few very popular systems will eventually make integration and electronic data transfer easier and therefore more likely. The stage is being set for increased integration.

PSMJ CADD Application and User Survey

A second survey of CAD use, one focusing on CAD use by design firms, has similarly interesting results (PSMJ 1989). Among the many findings of this survey, the following have particular relevance to this research:

Respondents reported using CAD for only 50% of their projects and even on those projects they use CAD primarily for drafting and do not use CAD to its fullest capability. Since designers participating in this survey use CAD for only 50% of their projects, the potential for integration and/or electronic transfer of data exists on only the half of projects for which CAD is used. Further, since most designers still use CAD only for drafting, the value of their designs in an integrated environment is severely limited. Designers will have to use CAD on a higher percentage of their projects and they will need to take advantage of CAD's capabilities before more integration is realized and before more constructors are interested in using their design files.

Most respondents felt that CAD made them more profitable despite their inability to get clients to pay for CAD services. Most companies also planned to increase their use of CAD. Despite the fact that designers use CAD primarily for drafting, they still find it profitable. Perhaps contractors can also increase profitability by using CAD to automate their production of the many construction drawings they normally draft.

Respondents reported a wide range of productivity increases and those with the highest productivity increases reported higher levels of use by architects and engineers. Further, these companies use more of their CAD systems' capabilities. Architects and engineers who use CAD get more out of it than ordinary drafters who have been trained to use CAD. The architects and engineers know what is required in the design. If they also operate the CAD system, they can streamline the entire design process. Further, users of advanced CAD features benefit more than those who just use basic capabilities. Advanced features of CAD systems leverage the ability of the user. Those who use advanced features leverage the time their spend designing on CAD to produce better, more useful designs. Construction companies contemplating the use of CAD can learn from this lesson and train engineers to operate their CAD systems rather than just providing CAD operators.

Costs per workstation have dropped to the $15,000 range. Because of the highly competitive nature of construction, companies must watch project overhead very carefully. Expensive mainframe or minicomputer based CAD systems were not a viable option for construction firms. Many construction companies can justify workstations in the $15,000 range without jeopardizing their profits.

The PSMJ study discusses many other finding but these four support the notion that integrating design and constructions is becoming increasingly possible and that the technology has advanced so that progressive construction companies can take advantage of CAD.

Examples of CAD Benefiting Construction

The current literature offered few examples of using CAD during construction. A significant and growing body of literature, however, discusses improvements in construction resulting from the use of CAD to design a facility. Most of the discussion in the literature comes from a few prolific writers at several EPC contractors. These writers generally describe very advanced systems and, while their efforts towards total project integration lag behind their use of CAD, they all agree that their CAD-based designs significantly improve their construction operations.

CII Study

A study conducted by the Construction Industry Institute (CII) surveyed its members to assess financial and operational effects of automating design and construction (Ibbs 1990). Their members, mostly large owners or EPC contractors, are relatively advanced in their use of CAD to support their design and construction operations. The report identifies several significant ways in which CAD improves construction operations:

- better materials management resulting in fewer excesses or shortages;
- improved constructibility;
- improved scheduling;
- reduced rework and changes.

CII members report that the financial savings associated with these benefits alone justify CAD regardless of the cost or savings of designing a facility using CAD. The report also identifies other ways in which the use of CAD improves project integration but it does not mention any significant use of CAD during the construction phase; construction operations merely benefit from the earlier use of CAD.

Bechtel

Bechtel, Inc, one on the largest international EPC contractors, is a leader in the development and implementation of advanced technologies to support their design and construction efforts. Several of their managers closely associated with their automation efforts have written extensively about their developments.

3DM™

One of Becthel's early developments was a proprietary three dimensional modeling system for plant design called 3DM™. As several of their managers have written, their use of 3DM™ has improved their construction operations tremendously (Killen 1988, Cleveland 1987, 1989a,b,c, Ivany 1988). The accuracy of the design models and the ability to check the model for component interferences during the design phase significantly decreases field rework. Further, the model allows plotting any perspective views the construction forces want. This improves communication of the design to the field and reduces misinterpretations of the drawings. Although Bechtel has recently ported 3DM™ from Intergraph minicomputers to a networked PC environment, which they envision could have a node on a construction site (Cleveland 1989b), none of the authors discusses specific on site applications of this system.

Walkthru™

Following the development of 3DM, Bechtel saw a need to view design models dynamically so they developed Walkthru™. Walkthru™ gives the user a set of controls that allow him to move around or through the electronic model of the facility. While Bechtel originally designed Walkthru™ to be an interactive design tool, they immediately recognized its value to construction personnel (Cleveland 1989a). Bechtel now uses Walkthru™ routinely to plan construction activities (Killen 1988). On a nuclear power plant retrofit project, Bechtel used Walkthru™ to plan the rigging configuration for several complex vessels and components that had to be removed from the facility and replaced. Walkthru™ allowed them to check for interferences and determine the clearance of the components as they were removed through other parts of the facility. This application assisted project management in planning the operation and communicating the plan to regulators and workers (Ivany 1988). Although Walkthru™ allows Bechtel personnel to support construction operations, its use remains confined to their design offices.

Construction CAE

Bechtel has expanded use of their 3DM system further with the development of Construction CAE, another proprietary application they developed to plan, simulate and schedule construction activities. Construction CAE integrates 3D CAD models with scheduling packages, expert systems and commodity databases using advanced graphics workstations. This allows simulating the construction operations and recording the assembly sequence to generate project schedules (Simons et al. 1988). The system includes construction equipment models and allows the planner to include temporary structures or facilities to accurately simulate the construction environment. It also provides dynamic interference checking to validate proposed construction flows and equipment selections. The system integrates with other project management tools such as programs for cost and project control (Gates et al. 1989). This ambitious and innovative system integrates design and construction to a greater degree than any other system described in the literature or found during this research. According to Bechtel personnel interviewed during this research, the system is still in a testing phase. Further, its reliance on very advanced, expensive graphics workstations will slow its introduction to the field.

Stone & Webster

Stone & Webster is another large international EPC contractor. Like Bechtel, they have developed an integrated 3D modeling environment for design and construction. Several of Stone & Webster's engineers have written extensively about their system.

IPD

Stone & Webster's system, Integrated Plant Database (IPD), uses proprietary software to link IBM's mainframe 3D modeling systems, CATIA, with a relational database program, DB2 (Nevins et al. 1989). They have found that designing facilities in three dimensions enhances construction operations in several ways. First, they believe that the system allows their construction planners to view the proposed facility earlier and offer constructibility input before any production drawings are made. Further, using IPD, construction managers can prepare different perspective views of the facility to help the field crews understand the design. This improves on site communications and reduces errors. Their system also checks for component interferences to reduce confusion and rework in the field. Finally, while the system is mainframe based, Stone & Webster can place terminals anywhere, which will include construction sites (Reinschmidt 1989). The authors do not indicate whether or not they have placed terminals on construction sites or what additional benefits this would provide.

COMANDS

Construction Management Display System, COMANDS, is a software module that operates with Stone & Webster's IPD system to allow construction planners to simulate and plan construction operations using the electronic model of the facility (Zabilski 1989, Nevins et al 1989, Reinschmidt 1989). COMANDS integrates planning and scheduling functions and allows the construction planner to simulate alternate construction sequences. The construction planner assembles a construction sequence model by placing building components from "electronic laydown or storage areas" into the facility as designed. The system records the assembly sequence. Further, the system calculates from the model all materials quantities for areas or parts assembled, and using related data files calculates costs and defines work packages. These then are integrated with other project management functions. Stone & Webster has used this system effectively on power, petrochemical and water treatment facilities. While acknowledging the potential for on site use, the authors do not mention the extent to which the system has been used on site or any additional benefits they found by having systems on site.

Fluor Daniel

Fluor Daniel, Inc, another large international EPC contractor, has found 3D CAD beneficial to their construction operations. While Fluor Daniel has decided not to develop proprietary CAD systems, they have been a leader in implementing 3D modeling in their design efforts. Since they began designing facilities using their CALMA Plant Design System (PDS), and more recently using Intergraph's IGDS, they have identified major benefits to construction including reduced direct field labor due to fewer interferences and improved materials management due to automated materials take-offs, which are faster and more accurate than manual take-offs (Gatlin 1989, Breen and Kontny 1986). The authors do not discuss the use of CAD on site to support construction directly.

Black & Veatch

Black & Veatch's POWERTRAK system integrates project controls, engineering design and drawing creation (Hollrah and O'Brien 1989). POWERTRAK uses a centralized database to support eight application modules: project scheduling, project cost analysis, manpower reporting, procurement control, drawing control, engineering design, CAE and construction control. While this system is highly integrated and apparently could support construction in the same ways that other 3D modeling systems do, Black and Veatch, an architecture and engineering (A/E) firm, does not do construction. The article discusses the potential to transfer data directly to other project participants but it does not indicate whether or not this has been done. The article does not discuss any use of this system for field engineering applications.

Related CIFE Research

Related research for the Center for Integrated Facility Engineering (CIFE) at Stanford University suggests many ways in which CAD and other computer-aided engineering tools could support construction. This background research suggests that CAD provides the opportunity to include constructibility input more efficiently and to plan construction methods and sequences better (Tatum 1990). Further, CAD could allow the construction planner to plan subsequent activities based on work already accomplished or to minimize the effects of construction delays by planning work around disruptions. CAD also makes design information more accessible to the construction forces, which could improve coordination and feedback. Integrated CAD systems could also significantly improve quality assurance and quality control by tracking voluminous reporting requirements and associating them with specific construction tasks. This background provides an interesting perspective of where integration efforts may ultimately lead and it suggests research that is required to move the industry towards this goal. Unfortunately, this research does not provide specific examples of such systems in use or examples of firms that benefit from using their systems as suggested.

Potential Construction Site Applications

One Author's Suggestions

The literature review yielded only one reference that even suggested possible uses of CAD on a construction site to perform construction engineering design or drafting functions. This reference suggests a multitude of possible applications of CAD on site and benefits from giving the constructor access to the designers data files.

> The drawings and schedules produced by the design professionals rarely form the full complement of documents from which a project can be constructed by site operatives. After the main contractor has been appointed, it is common practice for a variety of new drawings and schedules to be made. These will include further design details, shop drawings, construction proposals, temporary work details, as well as further extractions of lists and schedules for procurement purposes.
>
> It is too much to expect that the designer's CAD model or drawings can be the source of all this additional documentation. However, the CAD system is certainly a source of some of it, including much of the dimensional framework for the project, of additional measurement required for construction purposes, of spatial layout, and outlines of the permanent works. In essence, <u>it could be the informational backdrop on which much of the the additional construction documentation could be hung</u>. (emphasis added)
>
> Let us now look at a few possibilities. Using additional design layers,the contractor could add temporary works, specify pipe runs more clearly, produce larger scale drawings of zones and then add more detail. He could annotate components with suppliers' names and order codes, define construction phases, mark elements that have been completed, and add site accommodation, plan locations for stockpiles, mark the extent of excavations, check out the site access routes, set out and measure the layout of security fencing and make adjacent property. Contractors always need a host of measurements which are never shown on the drawings supplied to them. These are almost random thoughts but perhaps they will provide some ideas.
>
> 3-D models could prove particularly valuable. Consider for example the interaction of two or more tower cranes on a congested site. These have to be able to pick up materials either from parked delivery vehicles or from site stocks, and supply them to a multitude of locations and levels. The cranes (and cables) must not come into contact with existing or adjacent construction, temporary works, or each other! (Port 1989)

Unfortunately, the author offers no actual examples of where constructors have gotten plans electronically and used them as he suggests. His suggestions provide important incentives for constructors to participate in an integrated construction environment. Finding and presenting actual examples of constructors using CAD to perform these sorts of construction engineering tasks to validate the benefits of CAD in construction (a major objective of this research) should encourage contractors to seek these and other benefits.

Related Research

Findings from related research at the University of Texas at Austin concerning the potential for improving construction with constructibility input offered during field operations indicate that, while the leverage of such suggestions is diminished, the benefits can still be substantial (O'Conner and Davis 1988). The researchers identified and described seven topics for which innovative construction methods could improve operations: sequencing work, using temporary materials/systems, using hand tools, using construction equipment, preassembly, temporary facilities and constructor preferences. Many of these topics coincide either with suggestions made by Port above, or will be discussed later as findings from this research. CAD is an eighth tool that improve construction.

Barriers to CAD

Other research concerning the difficulties that design firms had implementing CAD into their operations may also apply to construction companies as they attempt to implement CAD to support their construction. Among the major problems that design companies had were the failure to adequately plan their acquisition and implementation of CAD systems, the lack of internal and industry-wide standards, misconceptions concerning CAD capabilities, difficulties measuring the benefits of CAD and the need to address a host of organizational and behavioral issues raised by CAD (Mahoney 1989). While that research did not address problems that construction firms would have with CAD, it is easy to imagine that they would have many of the same problems. Just as architectural and engineering firms have had to learn from the manufacturing industry how to implement and integrate systems, construction firms can and must learn from the design firms to avoid making the same mistakes. Construction firms may suffer more than design firms from the lack of people oriented towards computer technologies, and they operate in an environment that is less conducive to the use of advanced technologies (Teicholz 1989).

Findings From Literature Survey

This review of the literature concerning CAD and its applications in construction leads to the following conclusions:

- Technology is not a problem in allowing construction firms access to electronic design information. The technology exists, its costs have become reasonable and it can be configured in a variety of ways to support construction.

- Design firms have blazed the path in implementing technology in the AEC industry and construction firms can learn from their experience.
- CAD use in the design phase of a project is increasing and therefore electronic design information is increasingly available to the constructor. The transfer of data to the constructor, however, is not yet automatic.
- Several of the large EPC firms have developed and begun to implement integrated project design and management systems that allow construction forces to access electronic design data. The literature does not indicate whether or not these firms use workstations on construction sites to explore possible uses beyond those envisioned by the system developers.
- The literature offers only slight speculation regarding the value of electronic design information to construction forces and offers no examples of constructors currently using of CAD on the construction sites.

Against this background, the remainder of this report discusses how some innovative constructors implemented CAD and how they use it to support and improve their construction operations.

CHAPTER 3

APPLICATIONS OF CAD IN CONSTRUCTION

This chapter reports the results of interviews in nine construction firms (two EPC firms and seven construction-only firms) to determine how they use CAD in their construction operations. Interestingly, the large EPC firms performed only pre-construction applications using advanced 3D modeling systems, while the construction-only contractors used less sophisticated 2D CAD systems on site to support field engineering.

The specific applications of CAD these companies have found for CAD are discussed in the four major sections of this chapter. The first section, **Pre-Construction Applications of CAD,** discusses the benefits large EPC firms enjoy in the construction phase of a project resulting from their use of advanced 3D modeling systems in the design phase. These benefits include allowing constructibility input early in the design process; checking for interferences before construction begins; calculating more accurate materials quantities; conveying design intent to the construction forces; and simulating construction.

The second section, **Applications of CAD During Construction,** describes how the construction-only firms have used 2D CAD to automate old processes and create new processes and products. Table 1 highlights the major applications discussed in this section.

TABLE 1: Applications of CAD During Construction

Automating Old Processes		New Processes and Products
Concrete Lift Drawings	*	3D Viewing
Formwork Drawings	*	Scaled Overlays
Concrete Placement Drawings	*	Borrow Pit Model
Precast Concrete Operations	*	Rock Bolt Analysis
Isometric Drawings		Equipment Access Analysis
Fabrication Drawings		Up-to-date Information
Layout Drawings		Claims Quantification
Shoring Drawings	*	Stockpile Management
Traffic Flow Diagrams		Plot in Appropriate Format
Scaffold Design and Layout Drawings		Integrated Materials Management
Construction Sequence Drawings		
Bridge Falsework Designs	*	
Survey Control Plans	*	
Modifications to Design Drawings		
Subcontractor Coordination	*	
Drawing Logic Networks		
Utilities Mapping		

(* indicates that CAD added capabilities in excess of just supporting drafting operations.)

Since no current publications address how CAD is or can be used in construction, each of these applications is described in detail. The hurried reader is encouraged to scan the boldface subtitles and read only those sections of particular interest.

The third section, **Benefits of 2D CAD,** analyzes the applications of CAD and identifies capabilities of CAD that fostered successful applications in construction. The final section, **Preliminary Findings Regarding Applications of CAD in Construction,** presents some early analysis of these applications of CAD and the use of CAD in the construction industry.

Pre-Construction Applications of CAD

Several large EPC firms use 3D CAD modeling systems extensively to design facilities. Their use of CAD in the design phase enables them to use their electronic design data to plan and simulate construction operations.

Planning

These firms use advanced 3D modeling systems to assist them in insuring that a proposed facility is designed for easy construction. This includes checking to insure that all components fit as intended, that components are accurately counted and specified and that the construction forces understand the designer's intent. The following sections discuss these applications.

Constructibility Reviews

One company that uses 3D modeling extensively has their construction forces review the design as it develops beyond the conceptual design stage. By including constructibility input early, the design manager can insure that the facility is designed for construction in the manner that their construction people want to assemble it. Using 3D models, the construction forces can see the facility as it develops and add their input throughout the design process, rather than waiting until the design is essentially complete. Few drawings are produced before the model is complete and verified, so the construction forces have a larger window in which to add their advice without affecting the production of contract drawings. Further, even when changes to the design are necessary, it is easier to change the electronic model than portions of the constructed facility.

Interference Checking

CAD also allows the designers to insure that all required components fit. Visualizing components in three dimensional space is extremely difficult and this contributes to many unintended conflicts or interferences. 3D modeling systems indicate interferences to the designer as he adds components to the model, so the designer can resolve them before prints are made or, more importantly, before they cause construction delays.

Two EPC contractors explained that before they adopted 3D modeling for their designs, they added an additional 3-5% of the construction costs to the project to account for rework causes by design errors. Using 3D modeling, these companies report that rework is typically less than 0.5 % of construction costs, and they have experienced some projects with no reported discrepancies.

Materials Take-off

3D models also offer the constructor accurate materials quantities for all bulk commodities as well as individual equipment and components. These materials take-offs can also be integrated easily with other project control systems. The same two EPC firms have also used the model to produce fabrication drawings for steel sections and piping isometrics and pipe spool sheets for piping systems. This eliminated duplicate design efforts by fabricators by taking advantage of information that was easily derived from the design model. It also allowed construction input so that sections were fabricated in accordance with the planned construction sequence.

Another company prepared all material quantity take-offs on one project, down to and including connecting bolts. They then purchased all material and contracted only for labor to assemble the components. On a $15 million mechanical subcontract, they said they had only $15,000 in additional material costs, and these were due to additions to the system. This experience reinforced their confidence in using CAD for detailed design and materials take-offs.

Convey Design Intent

Finally, one EPC firm used their 3D models to communicate their design intent. Their designers narrated a dynamic tour of a facility discussing the design philosophy of major systems as they were viewed. They recorded this tour on standard videotape using animation software. The field crews could then review this videotape to learn the design philosophy and determine if necessary changes complied with the design intent.

Simulation

Construction simulation gives the constructor a major new capability. Constructors have traditionally dismissed some problems as inevitable because they never have a chance to construct a facility twice or practice field operations. Advanced CAD systems give the constructor the power to do just this. They can construct the facility in the computer before getting to the field to insure that the design is constructible and that their work plan is feasible.

Many construction tasks can be accomplished in different ways using different equipment. 3D modeling systems, with appropriate additional software, allow constructors to view their proposed construction sequence dynamically. They can view critical sequences and reanalyze them under different constraints, so they can resolve construction problems on the computer rather than in the field. By moving equipment models, configured as they would be carrying or moving materials, around or through a facility the constructor can determine whether or not the intended sequence causes interferences.

While several firms identified in the literature have this capability, neither of the two EPC firms interviewed simulate construction routinely on current projects. Moreover, when they do simulate construction operations, they do it in the design office rather than in the field.

On Site Use of 3D Modeling Systems

The firms interviewed see potential in using their 3D electronic models on site to assist project managers; none of the firms have done this yet. One of the firms placed an advanced workstation with access to the design model on a construction site but the construction personnel were unfamiliar with the system did not use it. Another firm plans to place an advanced modeling workstation on an upcoming project. They speak optimistically of the potential benefits but they have have not done it yet. One manager at this company firmly believes that once the system is on site, the construction forces will develop many innovative uses for the 3D model.

Applications of CAD During Construction

All of the pre-construction applications of CAD discussed above occurred within the design office before construction began, and the construction crews had no new direct access to the design models or associated database information. This section, on the other hand, discusses applications of 2D CAD on construction sites. While 2D CAD is generally considered an electronic drafting device, the applications discussed in this section will add new perspective to the value of 2D CAD and its ability to support construction. All of these applications supported the construction forces directly and provided information they needed. Project engineers initiated many of these CAD applications to produce standard drawings for field crews. The examples also illustrate the use of 2D CAD to produce unconventional construction drawings as well.

Automating Old Processes

The following applications of CAD produced standard drawings that most construction firms produce manually. As will be noted, though, CAD added a new power to the process of producing these standard drawings.

Lift Drawings

Concrete lift drawings consolidate into a single drawing or series of drawings all design information, such as dimensions, embedments, blockouts or interfaces required to properly prepare and place a designated section of concrete. Generally, the project engineer who prepares lift drawings must review the contract documents to find all drawings that pertain to a given concrete section and extract and combine the pertinent information.

Conventional Application

One heavy civil contractor bought CAD to help them produce lift drawings. Typically, they would have a drafting section dedicated to producing lift drawings, but they thought CAD would improve their drafting efforts. They have learned many lessons using CAD to prepare lift drawings on a current project. First, they no longer believe that CAD saves them any time initially drafting a lift drawing. Project engineers still spend the majority of their time researching the contract document to identify all essential information and insure that subcontractors' requirements are also included on the lift drawings. Actually assembling the lift drawing is only a small part of the process. Subsequent changes, though, are much easier and quicker to make using CAD.

CAD also helps them detect interferences between components. The CAD operator draws all objects in the CAD environment at full size, which highlights conflicts. They have found several instances where the manually drafted contract documents showed an arrangement that looked correct, but when they entered the same information into their CAD system, structures did not fit as originally shown. Such discrepancies are common because drafters make mistakes scaling distances or labeling dimensions. In one particular instance, the manually drafted contract documents showed a set of stairs easily clearing the top of a perpendicular the wall, while the CAD version of the design showed an obvious conflict. The CAD user resolved the interference before it caused construction delays or rework.

Another contractor received all of the contract documents electronically, which helped them in preparing lift drawings. After their engineers reviewed the paper drawings, they called-up the a drawing from their file server and copied the information they needed to the new lift drawing they were preparing. Because the A/E formatted their drawings differently, this constructor had to re-scale before overlaying the different design data. The engineers who used CAD to prepare the lift drawings did not believe that CAD saved them any time because they still spend extra time finding drawings files and rescaling components. They maintain, though, that once they completed a drawing in CAD, it was fast and easy for them to make changes.

Formwork Drawings

Several general contractors prepared concrete formwork drawings using CAD. These contractors have found that CAD enables them to do much more than just draw the proposed forming systems; they can reuse standard form drawings, analyze various layouts, and control formwork tie spacing as required.

Formwork Detail Plans

One contractor used their CAD system extensively to design their concrete formwork. While they would have designed the formwork manually, CAD allowed them to explore different forming alternatives. They constructed several standard size "gang forms" that could be used in many places. In planning the formwork required for a designated concrete placement, the CAD user simply overlaid a drawing of the form onto a drawing of the section to be placed, as shown in Figure 1. They could then adjust the placement of the forms to maximize the use of pre-built forms and to identify sections that require special formwork. Further, they specified exact locations for the pre-built forms relative to control points so the crews could place the large gang forms correctly in a single step.

Additionally, as they placed the formwork overlays on the lift drawings, they could clearly see where required formwork ties conflicted with embedments or blockouts and relocate the ties to avoid these interferences. They also coordinated the location of formwork ties between adjacent placements to use pre-drilled tie holes and avoid drilling extra holes in the forms, thus extending the life of the forms. Such preplanning reduced uncertainty and confusion in the field.

Formwork Layout Plans

Another large general contractor recently completed a large turnkey dam construction project. The engineer designed a complex double, logarithmically curved (top to bottom and side to side) concrete arch dam. The contractor planned to place the dam with over 600 separate concrete placements or lifts; each lift was different. They faced an enormous challenge preparing lift drawings and designing the formwork for the 600

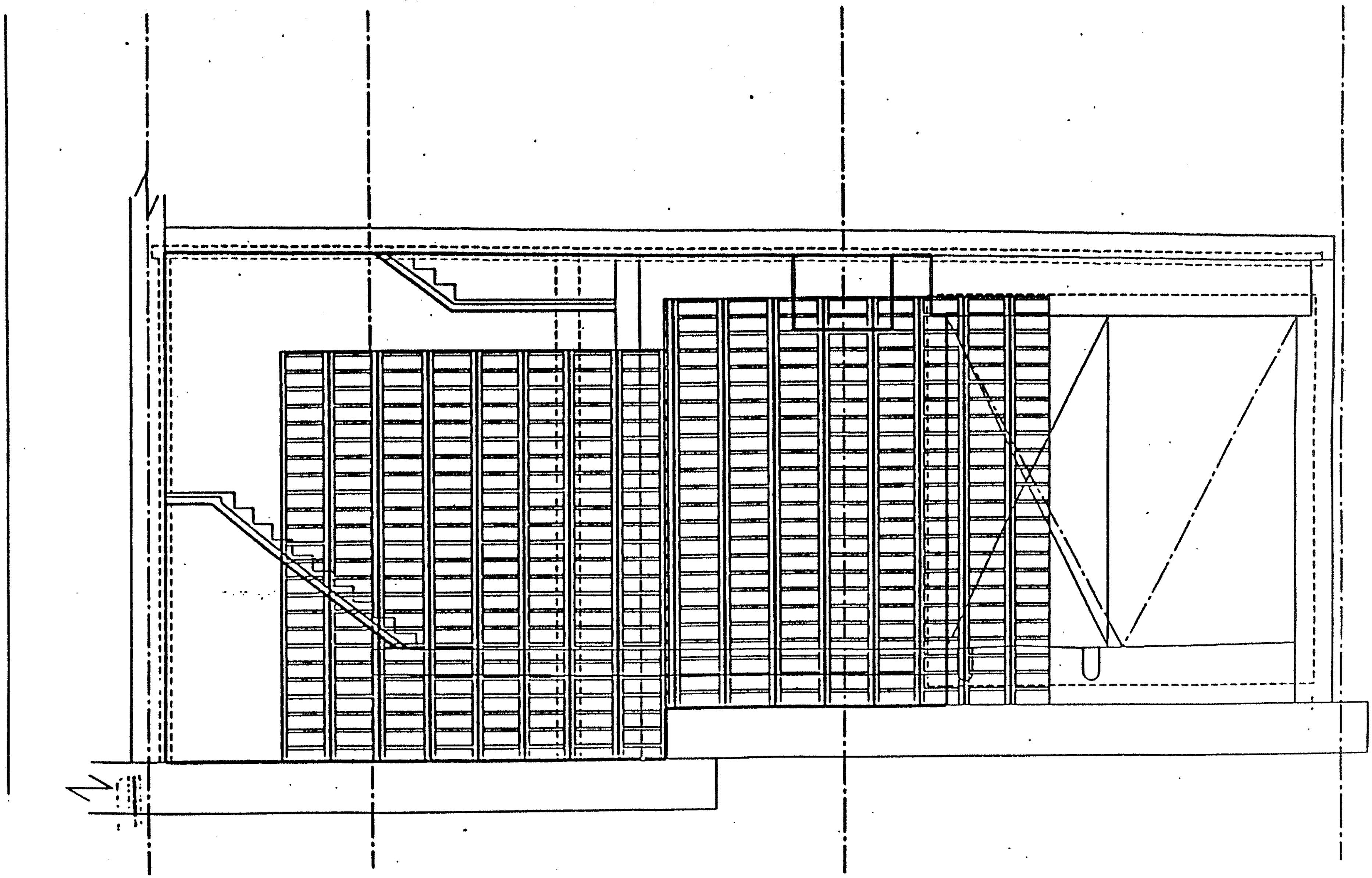

Figure 1 Form Reuse Drawing. This drawing shows how one contractor used CAD to design concrete formwork. Shown are two standard "gang forms" superimposed on a proposed concrete placement. The project engineer's next step would be to design the formwork for the areas still exposed. Alternatively, he could move the gang forms and have different areas to form.
(Source: Olsen-Ohbayashi Joint Venture)

different lifts. One senior engineer on the project and a CAD operator saw an opportunity to use CAD to simplify their task.

They devised a system that combined a program the engineer wrote in the BASIC programming language and AutoCAD. The engineer obtained the equations that defined the shape of the dam and used his program to calculate and format all the information that AutoCAD needed to draw each of the 600+ different lift drawings. AutoCAD could then calculate dimensions and offset dimensions for easy construction and quality control. The engineer insists that this system was essential to their success on the project because it was not feasible to produce the lift drawings manually; the workload would have been immense and the required for accuracy would have been difficult to achieve.

Tie Spacing Analysis

Another contractor used CAD to plan formwork placements so that the form ties created an architecturally appealing appearance. One approach to accomplishing this was to array the form ties in a geometric pattern. This contractor used CAD to view several different tie arrangements to insure that they would support the placement structurally and produce the desired aesthetic effect.

Concrete Placement Drawings

Concrete Placement or "Pour Drawings" indicate the order in which concrete sections will be placed and define the sections for which form and lift drawings must be prepared; most companies prepare them manually. Concrete placement drawings usually require considerable communication between the person who prepares the drawing and the field superintendent who must construct the final product. Using CAD, the person preparing the placement drawings can easily change the drawings to meet the field superintendent's requirements or desires.

An engineer at one contractor used CAD to plan and sequence concrete placements. He prepared a site plan in two dimensions and then added attributes to CAD database to designate placement numbers, section depths and placement dates. Using these attributes, he calculated the volumes of different sections easily and designated roughly equal size placements for different days to allow maintaining a constant crew and equipment balance.

An engineer with another contractor used CAD in a similar manner to calculate the areas for concrete placements. His supervisor wanted to plan equal size concrete placements and maintain a steady work force. While most project engineers would just divide the concrete plan views into roughly equal areas, this engineer used his CAD to calculate placement areas accurately. He tested five or six different placement configurations before selecting the final plan.

Precasting Operations

One project engineer relied on CAD extensively to plan and detail his projects' precasting operation. This engineer had to insure that 120 columns and 112 exterior panels were all accurately detailed, placed and installed. There were 12 different types of columns and 17 variations of panels.

The columns were extremely complex, some containing over one hundred embedments such as connectors for threaded rebar to allow continuous reinforcement into shear walls, shear plates, tubular blockouts at appropriate angles for post tensioning cables and lifting device anchors and reinforcing steel, as shown in Figure 2. Different configurations of these embedments existed in the 12 different types of columns. The columns varied in their overall height and in the location of corbels (seats for precast beams) in as many as three different directions at two different levels.

The engineer explained two significant benefits he derived from using CAD. First, since he detailed everything at full size, he could see interferences immediately and resolve those discrepancies before they delayed the project. Second, while overall dimensions of the columns varied, one dimension, the distance between corbels, did not vary; the differences were above the top corbel and below the bottom corbel. He used VersaCAD's associative dimensioning capability to modify the column designs. He only had to "click" on the dimension to be changed and type the new dimension, and the column was resized automatically. This simple but powerful capability made a time consuming task of modifying all the different drawings a relatively simple operation.

This engineer also used Microsoft Excel to calculate the dimensions of the columns. He received an elevation plan for the site and the layout grid for the columns from the structural engineer. He built a spreadsheet using this information and, using a macro program he wrote, the spreadsheet calculated the exact dimensions for each column. Then, using Multifinder on his Macintosh, he displayed this spreadsheet beside the CAD drawings. He changed the dimensions of the columns as indicated on the spreadsheet, saved the drawing and continued to the next column. With this easy reference system, he quickly produced plans that would otherwise have taken many days to draft.

This engineer also experimented with a new parametric design program that would allow defining a component in terms of variable dimensions. He would start by listing the dimensions in a tabular input form and the parametric design package would direct VersaCAD to draw the component to the correct size. He lacks only an interface between

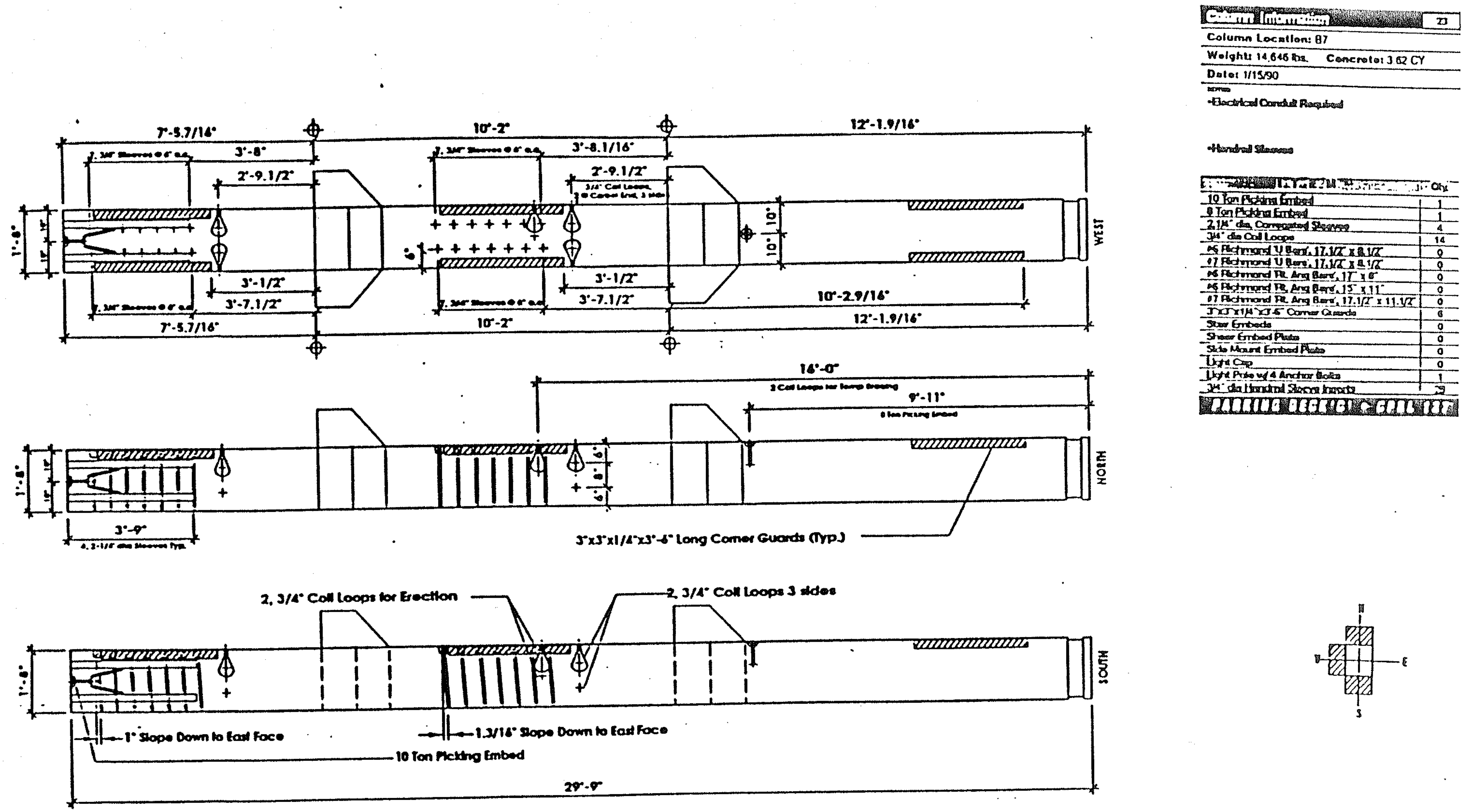

Figure 2 Precast Column Drawing. This drawing shows a precast column with a variety of embedments. The project engineer created a library of symbols for all possible embedments. He drew each symbol only once even though they appear in the drawing many times. This drawing shows three perspectives of the column so the engineer could accurately describe everything required in the column before precasting it. Changing the dimensions was very easy. The distance from the bottom of the column to the lower corbel is 12' 1 9/16" (top right). If, for the next column, that distance changed to 11', the project engineer only had to "click" his mouse on the dimension itself and type the new dimension; all three views of the column would be adjusted accordingly.

(Source: Charles Pankow Builders, Ltd)

the table of column dimensions that he created in Excel and this parametric design package to have a fully integrated/automated column design procedure.

Finally, the engineer established a library of the symbols that he needed for the columns and panels. Therefore, he was able to resize a column as required, place the appropriate embedments on the drawing and proceed.

Isometric Drawings

Another contractor used CAD to prepared isometric drawings for all flanged pipe on one its projects. They forward the isometrics to a fabricator who detailed and fabricated the pipe spools. In the past, they would have prepare isometric drawings manually. This is their first attempt to use CAD on site, and they also intend to use CAD to prepare lift drawings. Since they have CAD on site, they have found it useful for many other standard drawings such as layout drawings.

Fabrication Drawings

Another contractor prepared isometric and fabrication drawings. They used CAD to detail their required pipe spools themselves rather than having a fabricator detail them. Most constructors would send the contract documents to the fabricator to detail the spools. This contractor, however, detailed their own spools and just requested fabrication. CAD allowed them to dimension spools accurately, while accounting for all fittings, flanges, valves and gaskets. Further, since they detailed their own spools, the spools were fabricated to support their construction sequence, not a scheme envisioned by a fabricator.

Their detailing procedures also included a numbering scheme for all pipe spools and system components, as shown in Figure 3. When the components arrived on site, the construction superintendent could easily identify a piece and determine exactly where it belonged. This system had the additional benefit of allowing them to adjust their crew balance to include fewer expensive pipe fitters and more, less costly laborers. Their detailed designs reduced the construction process to an assembly operation, which required fewer skilled craftsmen than the traditional cut and fit process.

Layout Drawings

One general contractor used CAD to correct the layout of precast columns for a parking garage. The exterior panels still had to meet flush at all corners, despite the structures irregular footprint with several 45 degree turns. The project engineer used CAD to calculate the column offsets required to allow the exterior panels to meet as required. After establishing the exterior of the building, he placed the columns and oriented them correctly. Finally, he simply measured the offsets of the corner columns from the

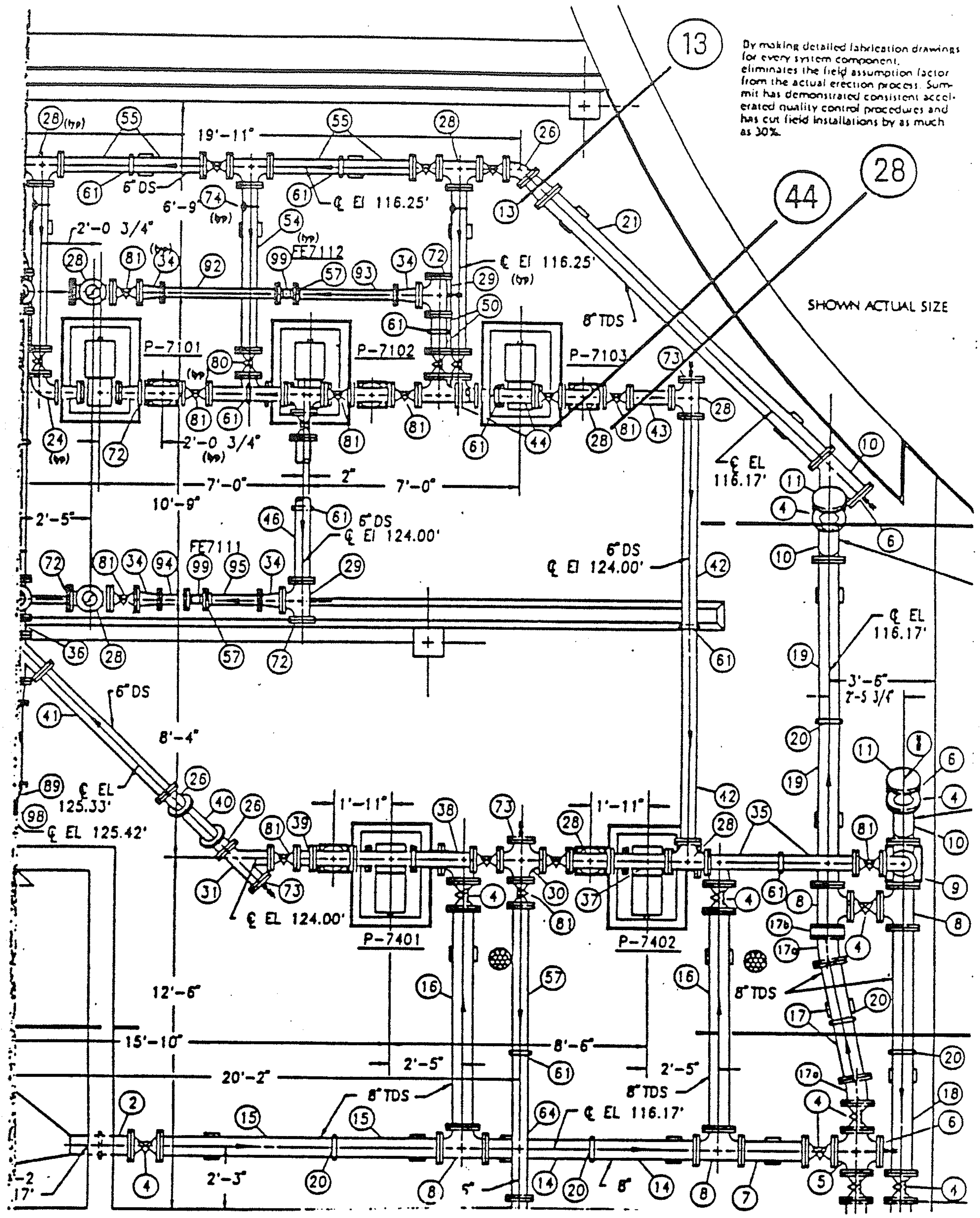

Figure 3 Pipe Fabrication Drawing. This drawings shows how one contractor detailed their piping systems for fabrication. They detailed their own pipe spools rather than having the fabricator detail them. This allowed them to plan their own construction sequence. The fabricator returned the specified pipe spools numbered for easy identification and installation. (Source: Summit Constructors, Inc. brochure)

orthogonal grid that governed the interior columns, using the CAD's automatic dimensioning capability, as shown in Figure 4. This application simplified the difficult task of calculating the offsets manually and highlighted the use of CAD as an excellent calculator. The engineer only placed objects at full size where he wanted them, and then measured to determine exactly where they were, a simple but powerful capability.

Another contractor also found that its site layout drawings are much more accurate and useful because they use CAD. First, since they can reuse backgrounds, a little extra effort creating background drawings pays dividends on different site drawings. They put less information on a given drawing to keep the presentation clear and avoid cluttered and confusing drawings. Producing extra drawings was a simple matter of turning different CAD layers "on" or "off" and replotting the file. Second, since they designed at full scale, they could see the relationship between all structures and facilities on site more clearly and accurately. They have found that accurately showing the relationships reduces construction problems.

Another contractor renovating an operational waste water treatment plant was required produce a series of layout drawings to convince the owner that the plant would remain operational throughout the project. Using CAD, they provided the owner with plans that it needed and also used the same drawing files for site layout drawings for their field crews. Generally, the layouts were the same but using different layers, the contractor provided different dimensions, details and notes to the owner than to its crews.

The owner has been very impressed with the neatness and clarity of the CAD drawings, and now expects the contractor to use CAD to maintain that quality. No formal requirement for CAD exists, but the contractor believes that manually prepared drawings are returned more frequently for changes or with questions while the CAD drawings are generally received better and approved faster.

Shoring Designs

A construction engineering consultant used CAD to design the shoring for a massive excavation. CAD yielded two major benefits. In designing the system, the engineer was able to try different column arrangements and spacings. The engineer who prepared the drawings said that if he had prepared the plans manually, he would have placed the piles a standard eight feet on center. Since CAD made changes very easy, he tested several different spacings for the columns to avoid oddly spaced piles or redundant piles at corners. Each pile costs approximately $1000.00 installed so by optimizing the arrangement, he saved several thousand dollars.

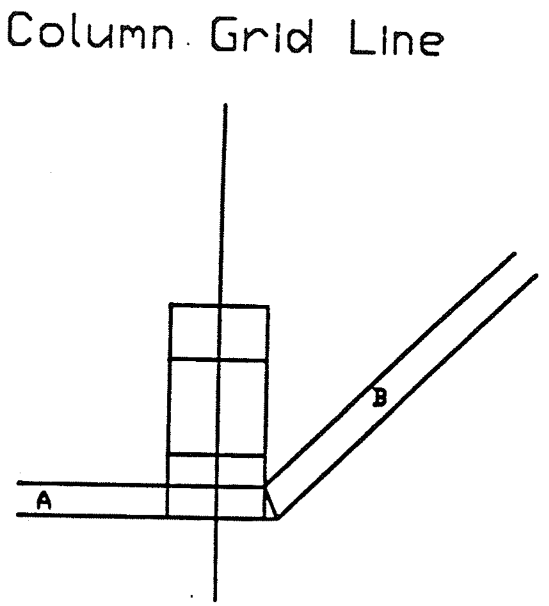

Figure 4a

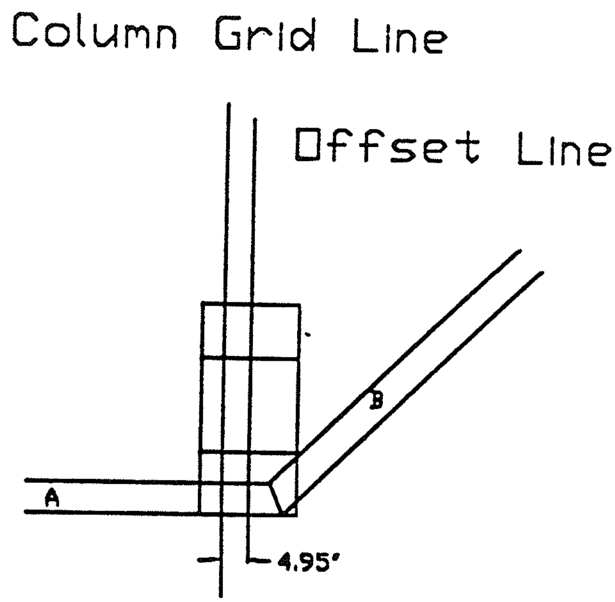

Figure 4b

Figure 4 Column Offset Calculation. This drawing shows how one engineer easily calculated the distance that a column had to be offset from a grid line for it to properly support two exterior panels. Figure 4a shows the original detail from the project plans. The column does not support panel B. The project engineer redrew the detail in CAD and then moved the column so that it supported both panels A and B. He then calculated the offset from the grid line so they could place the column on the ground properly.

Further, the engineer originally designed the shoring using all soldier piles with planks between them. The contractor requested changes so they could use sheet piles that they already owned. Since the engineer had used CAD, he could easily change parts of the shoring system to use the materials the contractor had without having to redraw the entire plan.

Traffic Diagrams

One contractor used CAD to produce traffic flow diagrams required for a project in a congested urban area. City officials would not let the contractor close either of two streets affected by their work during the work day. Before the city allowed the contractor to begin excavation, the city had to approve the excavation sequence plan to satisfy themselves that traffic interferences would be minimal. One project engineer prepared a set of traffic flow diagrams for a 12 block area surrounding the site on which he superimposed proposed traffic flows during different phases of the excavation. City officials were impressed with the planning and presentation but required some slight modifications. The engineer made the changes and returned the plans to the city officials the same day. The project's two assistant managers believe that this rapid turn around coupled with the high quality of the documents impressed city officials tremendously and laid the basis for good communication and relations.

Scaffold Design and Layout

An engineer for another company had previous experience using CAD in designing scaffolding supports. He created a scaffolding symbol to assist him in planning the required bracing for the supports. When the symbols were configured to certain spacing, a mark appeared on the symbol indicating that the unbraced length had been reached, which then caused him to add appropriate bracing. He indicated that such a cross check was very important since many bridge failures result from improper bracing and subsequent support buckling. CAD allowed him to make the check automatic, which enhanced his productivity and reduced errors.

Construction Sequence Planning

In another CAD application, the same engineer, consulting for another company, produced a set of working drawings that showed the sequence of work for a complex tunnel paving operation. CAD made the production of detailed working drawings a rather simple matter of moving components within a drawing, adding specifics where necessary and adding explanatory notes, as shown in Figure 5. CAD saved this effort considerable time because of the ease with which components can be copied and/or moved.

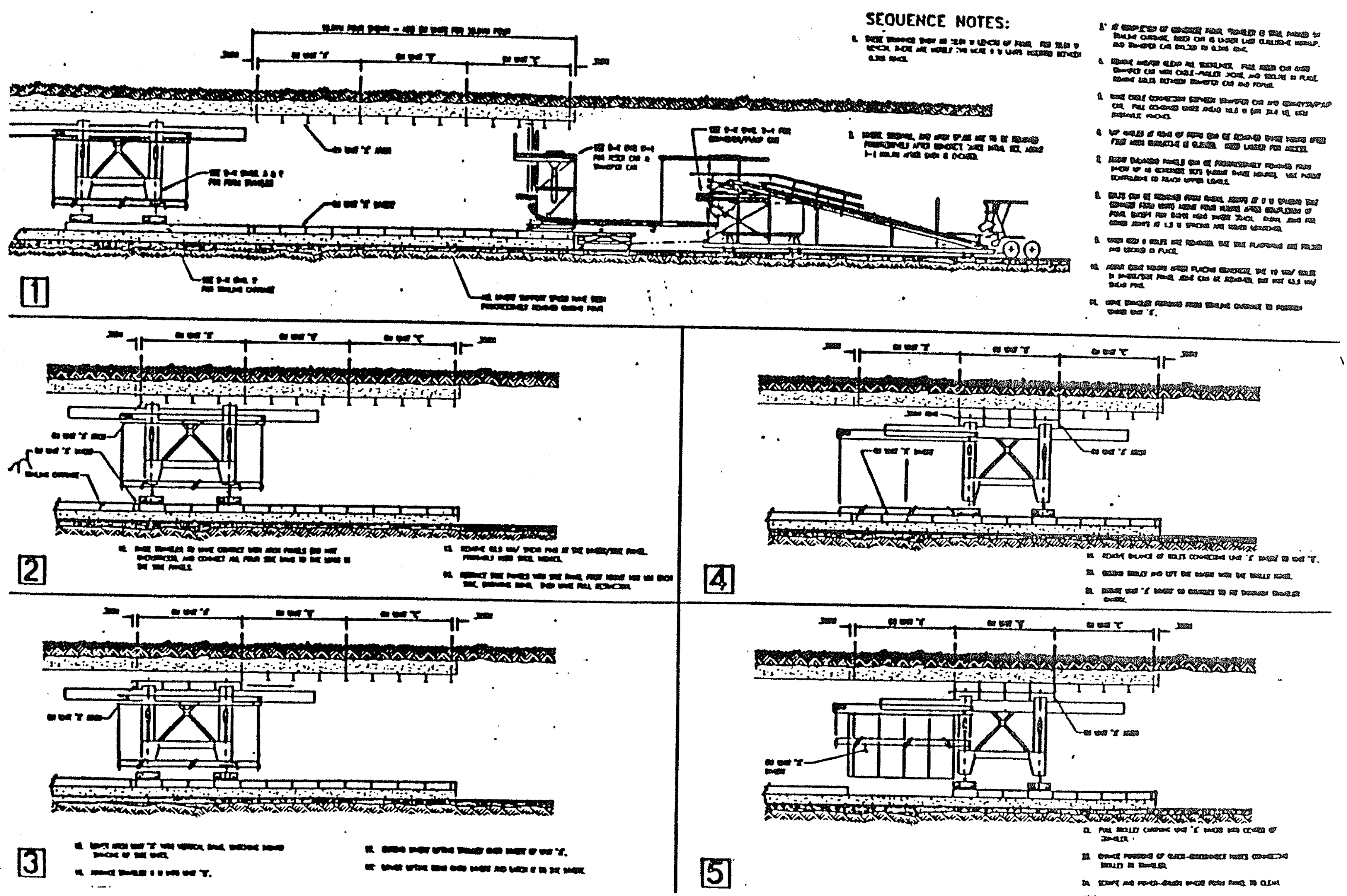

Figure 5 **Construction Sequence Drawing.** This drawing shows the construction sequence for a tunnel lining operation. The project engineer copied all of these drawings from one original. He then moved components within the drawing as required and added appropriate notes to explain the operation. (Source: Mike McTeer, Appendix F)

Bridge Falsework Design

This engineer also worked extensively detailing bridge falsework. He developed several libraries of symbols that specifically supported the use of CAD to design bridge falsework. He found CAD useful in several new ways. On one project, he designed the falsework for a complex parabolic bridge support. Using CAD, he was able to detail the falsework simply and accurately. The bridge support, though, was high and the contractor wanted an extra margin of safety for their work, so they plotted the basic designs of the bridge support, the element that their falsework had to support, at full size, 1 in equals 1 in. They then laid the entire bridge support plans out on a large parking lot and precut and assembled the falsework. This allowed them to work at ground level and insure that all pieces fit. This same operations would have been much more difficult and dangerous in place fifty or one hundred feet high.

In addition to drafting, this engineer also used CAD to assist in the design of bridge falsework. In one instance, he used CAD to help him calculate all column loads. First, he drew a cross section of the bridge, then he designated tributary areas of the structure loading each of the columns. He then added parameters for materials properties and depths of structures and wrote a macro equation that directed the CAD system to calculate the column loads. The owner of one project required the calculations of column loads on the falsework before construction began so they could verify the falsework design.

In a similar application this engineer used CAD to assist in designing camber shims. In designing the falsework for a bridge with a vertically curved road surface, he had to account for the use of straight bridge girders, bending deflection of the girders and settlement of the falsework under load. He used CAD to plot curves representing the proposed road surface, the deflected beam elevations and the settled falsework. He then calculated the size of the camber shims required at any location to insure that they achieved the designed road elevation. Manually performing the same calculations would have been very difficult and time consuming.

Survey Control Plans

CAD systems can easily, quickly and accurately show grids for project sites using either polar or rectangular coordinate systems.

Polar Coordinates

One contractor used CAD to generate complete survey plans for their project. One of their project engineers wrote a AutoLisp macro routine for AutoCAD to calculate control point locations. The surveyor simply indicated a point on a drawing and assigned it a control number; AutoCAD calculated the coordinates of the point. After the surveyor designated all the points he needed, he downloaded the control information directly from AutoCAD to an electronic field book that attached to his survey instrument. After he set-up his instrument, he accessed the control point by number and the instrument gave him an azimuth and distance. Locating the point on the ground was then a simple matter.

Rectangular Coordinates

From their CAD-generated site layout drawings, another contractor easily generates site survey plans for its field crews. Recently, they constructed several sludge digesters on a waste water treatment plant and found that they could easily produce an orthogonal layout grid for the digester based on the center of the tank. These grids allowed the field crews to set accurate string lines and place forms or components quicker and more accurately.

Accommodate "Or Equal" Equipment

Most specifications for the public facilities that one contractor constructs allow them to select equipment to meet general performance criteria. The contractor must reconfigure any parts of the associated piping systems to accommodate the different geometric dimensions or support requirements of the equipment they select. They would have done this manually but CAD offers them several advantages over manual procedures. First, CAD requires that they draw a component only once. Thereafter, they can copy the component quickly, easily and accurately. Further, although they do not design in three dimensions, CAD allows them to copy dimensions between different perspectives to maintain the integrity of the design in different dimensions. Their head designer and his CAD operators do not believe that CAD saves them much time in the initial drafting effort because most of their time is spent searching for relevant design information in the contract documents. They do maintain, though, that they benefit when they can reuse parts of a design or when they must change drawings.

Subcontractor Coordination

The only building contractor the researchers found who used CAD in their work employed a CAD consultant to produce a series of background drawings for different parts of a building on one of their projects. Once these drawings were prepared, the contractor was able to make changes as required and to provide current information for the subcontractors. Their prior experience has been that subcontractors frequently work off of outdated plans. Different subcontractors often use different outdated information.

Their use of CAD allowed them to give each subcontractor customized drawings that included only the information that they needed. For example, their plumbing and pipefitting subcontractors needed to know the locations of walls on and below a given floor, so that they could conceal all vertical runs of pipe in the walls. The HVAC subcontractor, on the other hand, only needed to know the locations of the walls on a given floor because they confined all vertical ductwork to utility shafts and provided all service at a given floor horizontally. Further, the HVAC subcontractor needed information concerning ceiling fixtures so that he could place ductwork appropriately, but the plumbing subcontractor was not concerned with reflected ceiling details. By layering information within the CAD files, the CAD consultant provided customized plans for each of the subcontractors. The piping subcontractor's plans showed walls on and below the floor while the HVAC subcontractor's plans showed the walls and reflected ceiling plans for the floor. All of the information that each received was coordinated in the CAD files but each received only what they needed.

Preparing such customized plans simply required the CAD consultant to replot the file with different layers turned either "on" or "off," as shown in Figure 6. Further, as the CAD consultant worked up from floor to floor, he could copy information from lower floors; he never had to redraw information twice but he could use it on different plans. Initially the subcontractors balked at the contractors insistence that they pay for the CAD drawings but the project manager maintained that the subcontractors acknowledge the value of the consistent, up-to-date information they received and that they would willingly pay for it again.

Prepare Logic Networks

Actual network drafting

Two contractors used CAD to draw logic networks for their CPM schedules. One contractor used several different scheduling packages that did not have good presentation capabilities. The networks that they produced were logically correct but very hard to follow. To make the networks easier for their field personnel to read, one project manager had the design section draft the networks on the CAD to present the construction logic and schedule information more clearly. This made updates easier but it distracted the design section from more important design activities.

Large scale plotting for ease of use

Another contractor found that scheduling activities benefited from on site plotting capabilities. The output from their Primavera schedule using a standard laser printer was small and hard to read. Now they use an electrostatic plotter to print "D" sized schedule

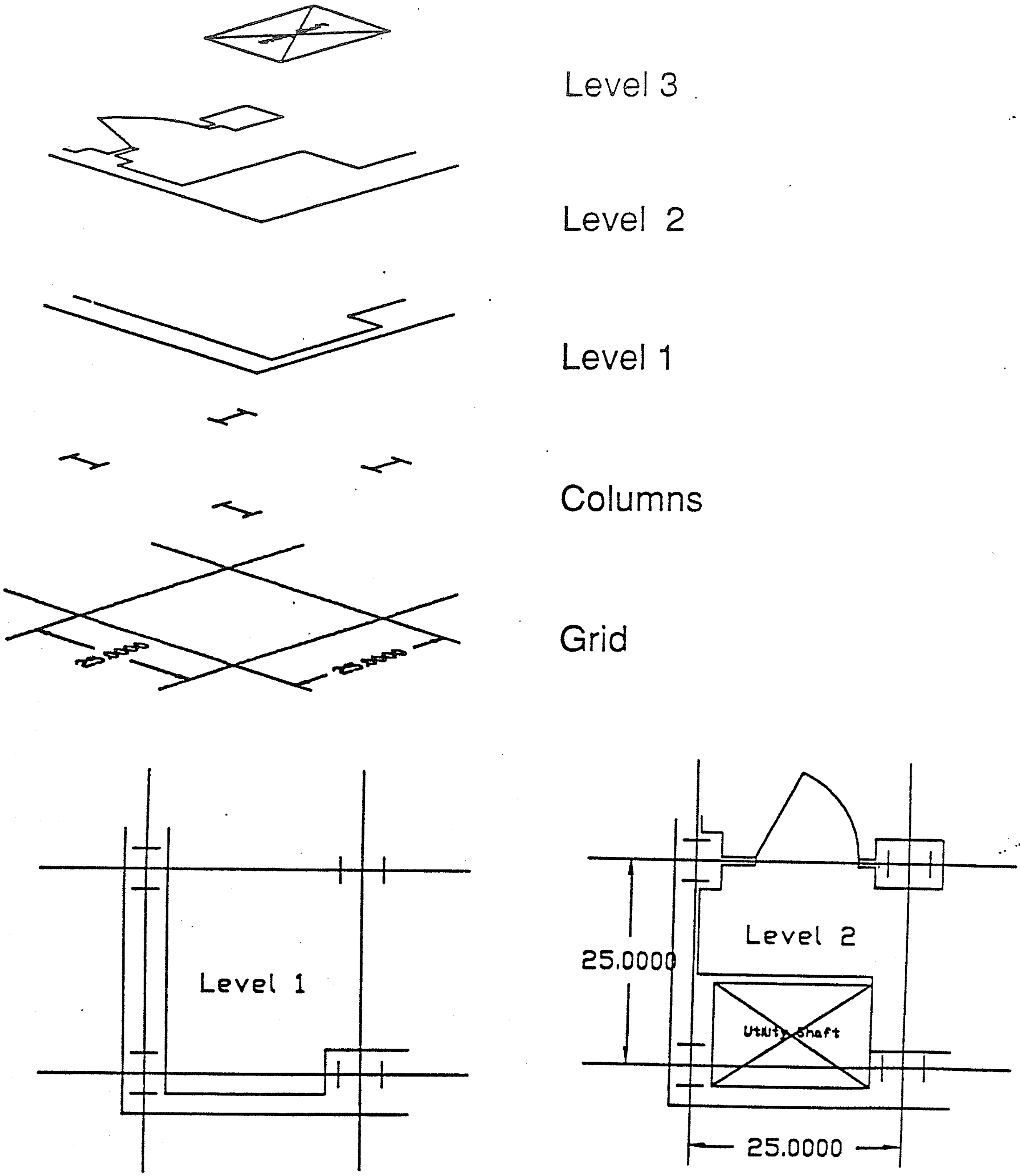

Figure 6 Layering Drawing. This drawing shows how a CAD operator may use different layers in CAD. Figure 6a shows several different layers within a single drawing file. Figures 6b and 6c were plotted from the same drawing file with different layers turned "on" or "off." This layering approach allows CAD users to filter information and customize drawings.

sheets. These allow grouping concerned project management personnel around the schedule, or logic network, to modify or trouble shoot the sequencing. They believe that this has significantly improved their communication of schedule information.

Rerouting Existing Utilities

One contractor found CAD useful in planning and documenting their efforts to reroute existing utilities on a project, a major activity that ran concurrently with excavation work. It was important to reroute the utilities so that they would not interfere with later construction operations. They used CAD to coordinate proposed new routes for utilities with both temporary and permanent structures on the site. The dimensional accuracy of CAD assisted this redesign application.

Filtering Information

One project manager maintains that one of the primary function of field engineers and shop drawings is to filter information for the field crews, to insure that the crews have enough accurate information to accomplish their tasks but not to much to confuse them or overwhelm them. He believes that CAD supports this goal very well. They can copy information easily to present a series of drawings detailing a specific task, and they can use layers to control exactly what information is displayed for a given sequence drawing. Providing clear, accurate and consistent information is essential to keeping the field crews working productively.

Another contractor decided that the shop drawings they were required to submit to the construction manager did not require the same information that the crafts needed to properly construct the facility. CAD allowed them to provide the right information to the right people. The shop drawings they submitted for approval had to clearly show the sequencing of operations and the interfaces with other parts of the project. The addition of the dimensions that the crews needed made these drawings cluttered and confusing. Conversely, the crafts were not worried about interfaces with other parts of the project, just the tasks at hand. The contractor used the same background information and overlaid additional details required by different users. In this way, they provided shop drawings for review that were clear and uncluttered and with minimal additional effort, they were able to provide drawings to their crews that conveyed the information they required to build the structure.

New Processes and Products

Like many other computer software products, CAD can be used in many ways beyond those envisioned by the developers. Indeed, perhaps the most exciting findings of this research are numerous examples of innovative applications of CAD to produce useful but unconventional construction information or drawings. Innovative CAD users have tremendous computing power at their finger tips, power that allows them to produce many fascinating and useful applications of design data in the construction phase. This power is limited only by they skills and the needs of their project.

3D Views

One contractor has several engineers who have begun to use 3D drawings to show complex details or configurations. Producing three dimensional drawings requires considerable extra time and, given the need for production, these engineers have little time to develop 3D models. This contractor does not plan to use 3D modeling representations extensively but, in several cases, the time invested saved valuable construction crew time by presenting plans in more understandable drawings. In one particular instance, an engineer modeled a portion of a complex tank support. The support had a set of irregularly shaped supports arrayed in a circle. The 3D model allowed them to explore forming alternatives and to design the formwork to simplify the placement as shown in Figure 7.

Scaled Overlays

Another project engineer used CAD to produce overlays to plan a clearing and grubbing operation for the placement of a utility trench. Prior to beginning construction, they had an aerial survey of their project site; the resulting photograph was plotted at a scale of 1 inch equals 100 feet. The site plans were plotted at a scale of 1 inch equals 40 feet. In manual practice, he would have had to correlate the two plots keeping them side by side. Using CAD, he simply replotted the site plans at a scale of 1 inch equals 100 feet and immediately had an accurately scaled overlay for the aerial photograph. He used the overlay and the aerial photograph together to plan exactly which trees had to be removed to allow placement of the trench. The alternatives would have been clearing an area larger than necessary, an environmentally unsuitable alternative, or sending a survey crew to determine exactly which trees had to be removed, an expensive and time consuming alternative. CAD gave him access to the information he needed immediately, at no extra cost.

Borrow Pit Model

During the pre-bid stage of a project, another contractor created a 3D model of their proposed borrow pit to use in planning borrow operations. Their estimator entered the various elevations for the different materials at the different bore locations and was able to create approximate volumes for each type of material. From this model, they could plan use of the area to insure that they had the correct materials.

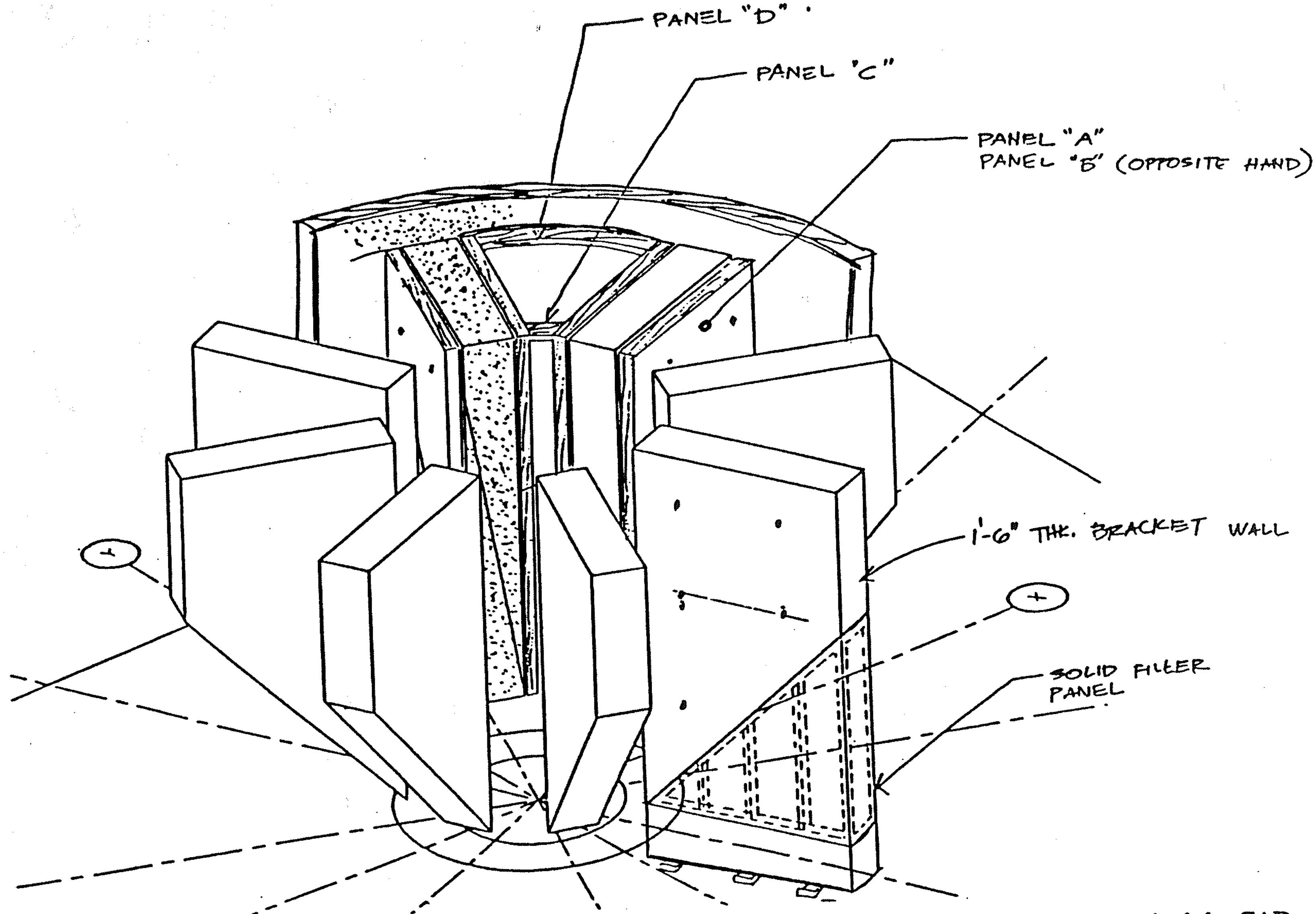

Figure 7 3D Perspective. This drawing shows a part of a support tank. The construction superintendent asked the CAD operator to generate a 3D perspective of the support configuration to assist him in planning the formwork for the concrete placement. The CAD operator modeled the eight wedge shaped concrete supports and added the polar coordinate system. The superintendent then sketched how he wanted to form the difficult placement. This perspective allowed the superintendent to visualize the placement better and plan the formwork more accurately. (Source: Olsen-Ohbayashi Joint Venture)

Rock Bolt Analysis

Another contractor recently constructed a new set of locks at an existing dam. One wall of the locks required anchoring to an adjoining rock cliff with over 2000 rock bolts. All the contractor received from the engineer was a list indicating the type of rock bolt required at specific locations. The raw data they received was of little value because it was nongraphical and hard for the crews to relate to specific concrete placements. The contractor entered the information into a 3D CAD model of the locks.

This effort yielded two important benefits. First, it related the different rock bolts to different concrete placements so that construction personnel could properly plan the placement of the bolts in conjunction with their concrete lifts. Perhaps more importantly, the CAD model showed that more than 5% of the rock bolts, over one hundred, were improperly designed; in many cases, the specified bolts missed the rock face altogether because the designer did not account for the slope of the rock face in relation to the locks. By detecting the improperly designed rock bolts before construction, the contractor was able to resolve the problems early and avoid costly delays and potential claims.

Equipment Sufficiency and Access

Another project engineer found CAD very useful planning the placement of a high angle conveyor (HAC) on a subterranean urban project. This conveyor system removed spoil from the excavation vertically through a small opening left in the road planking to a street level hopper. The HAC arrived on site in several pieces and had to be assembled. The project engineer drew the modular pieces of the HAC using the CAD and easily created layout drawings for the entire HAC system. Both the HAC and the hopper were very heavy and required support under all points of contact. The engineer used CAD to coordinate the placement of the heavy girders that supported the roadway planking and these heavy components. Drawing all elements at full size simplified the design process and eliminated the potential for errors from scaling.

Another contractor won a contract for work far from their home office and needed to know if a modified Caterpillar 245 excavator they had nearby could fully excavate a specific trench and load haul trucks according to their proposed plan. They hired a CAD consultant to draw several views of the trench, the excavator and the trucks to statically simulate the operation. CAD allowed him to copy and rotate the excavator arms to show its actual reach from any position, as shown in Figure 8. This analysis convinced the project manager that their excavator would be able to perform the necessary work and that they would not need to haul one of their larger excavators to the project or rent one in the area.

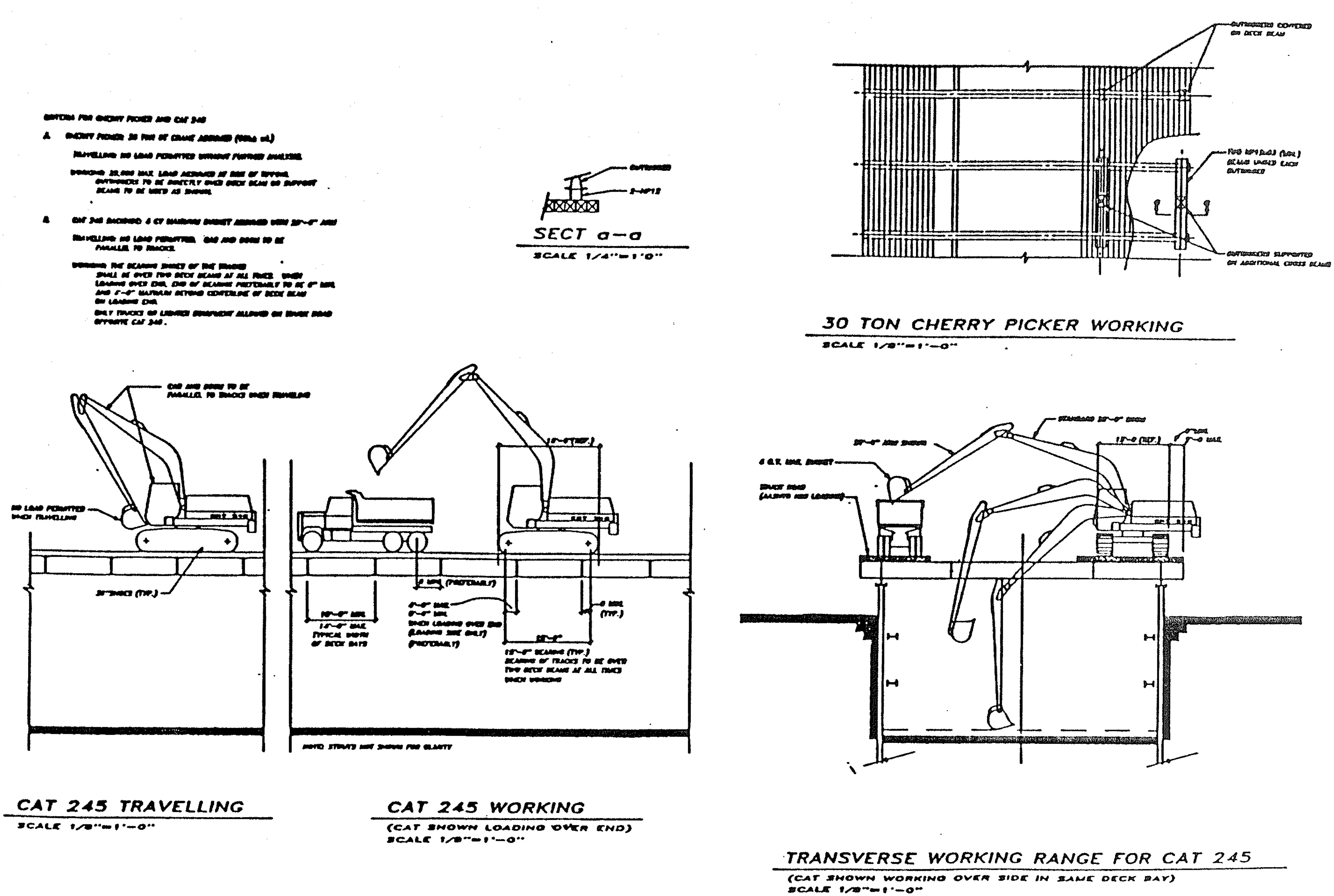

Figure 8 Excavator Drawing. This drawing shows a static simulation of a trench excavation. A CAD consultant drew the trench, the excavator and the truck at full scale to see if the excavator could fully excavate the trench. He then copied and rotated the excavator arm to simulate its reach in the trench. Since the operator drew the objects at full scale, there were no scaling problems and he could be sure that the excavator could accomplish the task. (Source: Mike McTeer, Appendix F)

Up-to-Date Information

Everyone interviewed at one contractor agreed that the primary benefit they received from CAD systems was the ability to provide accurate and up-to-date information to their field forces. With their project 10% complete, they generated 800 Requests for Information (RFI's). Of these, 80%, or over 600, required changes to shop drawings. They were frustrated that their initial drafting efforts realized no improvement from CAD but they have found that the changes required by the RFI's are quick and easy. They averaged three days to post changes required by the RFI's to the appropriate drawings, but they could make changes immediately if required. Recently, an inspector stopped a foreman to point out a discrepancy between the work the crew was doing and his set of plans. Upon further investigation, the foreman found that he was working from the correct, most current plan while the inspector's plans did not reflect several important changes. Insuring that the field crews have accurate and current information greatly reduces the potential for errors and consequent rework.

Integration with Aerial Survey

Claims Quantification

One contractor found CAD useful documenting a claim for extra work. The contract documents they received from the owner guaranteed certain elevations when they began work. When they arrived on site to begin work, they found that the a previous contractor had overexcavated the site, requiring them to place an engineered fill in certain areas under structures they would construct. The project superintendent quickly identified and quantified the problem using CAD. He digitized information from an aerial survey and then overlaid that information with site plans reconstructed from the contract documents. This combination of data clearly showed the extra amount of work that the contractor had to perform.

Stockpile Management

The same contractor also used CAD with an earthwork takeoff software package to plan their basic approach to the project's extensive excavation, and they are currently using it to plan backfill activities that are several years away. In planning the project and preparing their bid, the contractor had two basic options, on site stockpiles or off site storage of excavated material. Off site storage required hauling and later backhauling the excavated material, and would have cost $5 million more than on site storage. They used an earthwork takeoff package with their CAD to establish that there was room on site for a properly designed stockpile. They also used CAD to plan the stockpiles to prevent interference with construction operations.

They also plan to have a second aerial survey done in the near future. From this survey, they will determine the exact size of their stockpiles. By overlaying the survey information on the final site plan, CAD can calculate the volume of the stockpile and the amount of material required to backfill after construction is complete. Knowing the difference between their supply and their requirements, the contractor will be able to plan for the future. If they are short, they can identify sources for fill and contract for necessary fill at the best prices over the next few years; if they have too much, they can sell some of the fill. Using CAD and the aerial survey data, these calculations will be quick and easy and allow planning activities years in advance. Without CAD, such planning would never be done and they would wait until the end of the project to see if they had enough fill and possibly get caught short and have to buy fill in a tight market.

Plot in Most Appropriate Format

One project engineer used CAD to produce unconventionally sized drawings that were convenient for on site use. They did not have a plotter on site, so the engineer was limited to a standard laser printer. He plotted each drawing in two halves and then combined the halves using the office copy machine to produce a single 11"x17" drawing He then placed the drawings in notebooks, a convenient format for carrying around the project site. He found that this format kept the plans neat, clean and useable throughout the project. This engineer turned a constraint into an asset.

Integrated Materials Management

On a bridge falsework design project, one project engineer wrote a CAD macro routine to track materials. His routine allowed him to create materials lists for the falsework he designed or to work backwards from existing materials lists to design the falsework. The engineer felt that this capability was important because it prevented contractors from spending extra money on new materials. Perhaps more importantly, it allowed the crews to build the falsework as designed rather than improvising to employ materials on hand, a process that could lead to falsework failure.

Benefits of 2D CAD

By analyzing these applications of CAD on construction sites, the researchers have identified important capabilities of CAD that fostered successful applications. Understanding the capabilities described below will help other constructors use CAD to support their construction efforts more effectively.

Copy and Reuse Drawings

Perhaps the most basic benefit that CAD offers any drafting effort is ability to copy information or drawings. CAD users draw symbols or components only once and then copy them as often as required to complete a drawing. Drawings or components are copied accurately, consistently and quickly to maintain the integrity of the design. More advanced CAD users extend this capability to develop libraries of symbols or drawings they use frequently, so they can reuse symbols or components on different drawings or on different projects. They can also place those symbols in a central file server for others to use. Finally, CAD users can create standard backgrounds of facilities so that designers from different disciplines can all access the same basic design.

Easy Changes

CAD users can change drawings very easily. Changes may reflect revised design intent, conflicts that arise when the designs of different disciplines are compared, changes for constructibility or changes to accommodate variations in equipment or construction. People interviewed during this research maintain that 30-50 changes per drawing are not uncommon. The ability to make so many changes quickly and easily, therefore, is an important benefit.

Clarity and Consistency in Presentation

CAD draws lines or shapes sharply and formats text and numbers clearly and consistently and they remain clear and accurate. One company had a problem with a manually prepared drawing. A detailer mistakenly labeled a dimension 1 0" rather than 1'0". The field crews interpreted the dimension as ten inches rather than one foot, a difference of two inches. This error caused misplacement of the anchor bolts for a turbine generator by two inches, a significant construction problem. Such an error would not occur using CAD because the system automatically calculates, formats and displays accurate information clearly and consistently.

Layering Information

CAD users can layer information within a drawing file for efficient viewing and plotting. Layers can be thought of as transparencies containing different information which are laid on top of each other to create a drawing. The viewer can turn layers "on" or "off" to view specific information without confusing information in the way. The CAD user can also plot drawings with certain layers "on" or "off" to prepare drawings with less information that are clearer, less cluttered and easier to read or to meet the specific needs of the intended user.

Full Size Representation and Interference Checking

Objects are represented at full size using CAD. The CAD environment can be adjusted so a semiconductor chip designer can work in microns or a city planner can work in miles. In most cases, the designer and constructor would draw facilities in feet and inches (the user can easily switch to metric units). If a designer wants a line eight feet long, he draws a line in CAD that is "eight feet long." Although it appears shorter on the computer screen, CAD stores the dimensions of the line as eight feet, and when the line is dimensioned or referenced, CAD will show its length as eight feet, regardless of the plotting scale. Since all objects are drawn at full size, CAD drawings maintain the actual physical relationship of objects, which allows even 2D CAD to offer a limited ability to check for interferences between objects in a drawing.

Symbols on drawings that have no physical significance must be scaled for the intended plot scale but this is simple to do on CAD and a much smaller problem than correctly scaling physical objects. Many of the people interviewed felt that scaling was one of the most difficult parts of drafting and that eliminating the need to scale objects improved the speed and accuracy of their drafting.

Improved Accuracy

Like any calculator or computer program, CAD can calculate dimensions to many decimal places. Often such accuracy is unneeded or misleading, but problems can be avoided using formats that round numbers and/or allow for tolerances. Accuracy is significantly enhanced by CAD's ability to correctly identify line intersections or points on a curved surface. An engineer scaling distances off of a paper drawing can only approximate distances, while CAD can generate dimensions quickly and accurately. The companies using CAD have found that once their construction forces understand how quick and accurate it is to add more dimensions, they ask for many more dimensions to check their work.

Super Calculator

CAD can also plot complex shapes and accurately calculate the distance between points on those complex curves or surfaces and any other curve, line or surface. Using this capability, a CAD user can provide additional information to construction crews about how to layout and construct complex components. For example, a CAD user can simplify the construction crew's task of laying out a curve by establishing a chord of the curve and then dimensioning evenly spaced perpendicular lines from the cord to the circular surface. This capability also allows designers to depart from standard designs with the confidence that they can provide enough accurate information to allow the constructor to build their designs.

Plot at Various Scales

The CAD user is not constrained to any particular sized output or any proportionately sized copy of their original. CAD allows the user to plot their drawings at any size, or to plot any part of their drawing at any size. Thus, the designer can plot entire drawings as official shop drawings and a field engineer could enlarge and plot a specific detail for the construction crews. Further, "D" or "E" sized plots may not be the most useful format; perhaps details plotted on an 8.5" x 11" sheets of paper would better suit needs of the field crews.

Blurs Distinction Between Design and Drafting

CAD blurs the distinction between drafting and design. The accuracy and calculating power of 2D CAD systems allow the drafter or designer to access or easily create important additional data. For example, the CAD user can change areas in plan view into volumes, which, in turn, he can use to calculate weights to determine column loads for supporting structures; CAD makes all of these calculations easy. The designer who merely supervises a CAD operator putting lines on a screen fails to take advantage of vast amounts of information and computing power available to him.

Customization

Most CAD systems include macro or procedural languages that enable users to program or customize the systems to automate specific tasks. This may include developing symbols libraries, developing parametric design functions or automating calculation intensive operations. Customization greatly leverages the design capabilities of the system. CAD users on two of the projects studied made their systems much more productive by programming them to support particular design functions such as calculating survey control points and calculating concrete volumes.

General Improvements to the Construction Process

In addition to the individual capabilities CAD offers the constructor, it also offers several general improvements to the construction process. These include improved communication of design data and intent, designs that support constructors rather than direct them and marketing advantage.

Improved Communication

Arguably, the most important responsibility of project engineers is to communicate the design intent to the construction forces. CAD improves this communication process in several ways. The clarity and consistency of the output from the both 2D and 3D CAD reduce misinterpretations and uncertainty in reading plans. Since changes are easy on both types of CAD, getting revised, updated plans to the crews is easier. 3D CAD can generate various perspective views of a structure or parts of a structure to provide unambiguous information to the field crews about what they must build. Clear, current and detailed information keeps field crews working efficiently.

Design for Construction

The use of CAD, especially 3D modeling, allows the construction crews to review the design and add constructibility input earlier. With CAD, construction people can see the structure earlier in the design phase when changes are still relatively easy to make. Further, CAD can calculate material quantities by area or system to best support the construction managers. Using either type of CAD, designers can detail components in a manner to support the intended construction sequence rather than adjusting the construction sequence to fit the fabrication process.

Marketing

Both 2D and 3D CAD creates a marketing advantage for companies that use them properly. Several EPC firms consider their advanced CAD capabilities as important strategic assets. They market their technological capabilities and frequently win construction contracts based on their advanced design capabilities. Smaller construction-only firms have been slower to market their CAD capabilities. One general contractor, though, highlights their use of CAD as a distinctive competence when competing for work with highly selective, private owners. In increasingly competitive markets, any advantage helps.

Findings Regarding CAD Use in Construction

Several general observations and trends emerge from the wide variety of CAD applications reported in this chapter.

Tasks Anticipated But Not Found

It is interesting to note that this research did not find examples of two applications of CAD in construction that have been publicized: preparing as-built drawings and estimating.

The As-built Myth

None of the firms investigated used CAD to prepare as-built drawings. According to many of the companies interviewed, the drawings that they produce using CAD take information from the contract documents and reconfigure it and combine it to suit their needs; none of the firms reproduced the contract drawings. Consequently, the companies red-line contract documents and report changes to the A/E as they did before they used CAD.

Estimating

None of the firms investigated used CAD in their estimating because they did not receive electronic data from the A/E before they bid. The researchers found only one general contractor who received electronic design data from the A/E at all, and this transfer occurred after the contractor won the job. Another contractor received a request for proposals for a project indicating that the contract documents were available electronically. When they tried to get the plans to assist their estimating, the A/E said that only the successful bidder would be allowed to purchase the electronic files. All of the companies interviewed indicated that they would like to use CAD for estimating but they believe that it will be difficult to get useful design files from A/E's.

EPC Firms

- While the large EPC firms have focused their efforts on expanding their use of CAD from their design office to simulating and planning construction, neither of the firms investigated has used CAD effectively on their construction sites. While those interviewed plan to move their systems to their construction sites, they have not identified any specific construction site or field engineering applications.
- These firms use advanced systems capable of integrating the entire design and construction process. Currently, they use their systems to integrate internal design and construction activities and they have limited experience integrating external organizations into their operations.
- The efforts of these firms to develop advanced systems has little effect on the rest of the construction industry.

General Construction Community

- The general contractors investigated during this research use CAD in two ways: to automate drafting procedures and to take advantage of the design capabilities of their CAD systems.
- All of these general contractors used 2D CAD systems that they initially bought to draft necessary construction drawings.
- Several general contractors have expanded their use of CAD from basic drafting into more advanced design functions.
- CAD significantly increases the flexibility of field engineering efforts.

- Even 2D CAD is a powerful tool, which innovative users can use to support and improve construction operations in ways that many people would not imagine.
- The contractors interviewed acknowledge that 3D CAD would provide significant advantages over their current 2D systems but they are not ready to make the investment of time and money to acquire those systems. Further, such use would only be efficient in an integrated construction environment.

CHAPTER 4

CHARACTERISTICS OF SUCCESS AND BARRIERS TO CAD IN CONSTRUCTION

This chapter analyzes the research data from a different perspective than the previous chapter. Rather than considering specific applications or capabilities of CAD, this chapter concentrates on how each of the companies implemented CAD. By analyzing these implementation strategies, the researchers have identified characteristics of successful CAD implementation and barriers to the use of CAD in construction. The first section describes how the companies studied implemented and now use CAD, to establish the context for the analyzing the characteristics of success and the barriers. The subsequent two sections discuss those characteristics of success and barriers. Finally, a framework for considering the costs and benefits of using CAD in construction is presented.

How Seven Construction Companies Implemented CAD

Each of the companies studied had a unique approach to implementing CAD, as described below. Each had to configure a CAD system (hardware and software) and decide where to place it. They had to determine who would operate the CAD system, how they would be trained and how their efforts would be directed. Table 2 summarizes how each company implemented CAD.

One company supports all of its construction projects with centralized CAD assets in their home office. They have three IBM PC compatible, 386-based computers, using AutoCAD in a stand alone mode. One of the machines is connected to a pen plotter for output. An experienced designer administers the system and supervises two CAD operators who joined the company with minimal CAD training and no construction experience. The designer initiated the company's use of CAD and his ability to experiment with the system and explore new capabilities controls the company's advancement with CAD. This designer coordinates with project managers to meet their requirements for construction drawings, but they know nothing about the CAD operation. Although the drawings he prepares are clearer and more accurate because he uses CAD, the designer produces basically the same drawings that he would otherwise have prepare manually; he has automated his process but he has not changed the process or the product of his work. This company has not received design information electronically from architects or engineers but they still believe that CAD improves their internal operations.

Table 2. Current CAD Configurations

Example	Hardware	Software	Operator	Project Size	CAD Location (1)	CAD Procedures	Libraries	Network	Administrator	Customized	Electrostatic Printer	Training (2)	Relative Success
1	1 PC	AutoCAD	CAD Operator	> $200 million	HO/PS				●	●		A	Moderate
2	1 Mac SE30	VersaCAD	Engineer	<$20 million	PS		●			●	●	B	Moderate/ High
3	1 PC	AutoCAD	CAD Operator	$50 million	PS							A	Low
4	2 PC	AutoCAD	Engineers	$50 million	PS		●			●	●	B	Moderate
5	3 PC	AutoCAD	CAD Operators	Variable	HO				●		●	A	Moderate
6	8 PC 1 SUN	Microstation AutoCAD	6 Engineers 2 CAD Op	<$200 million	PS	●	●	●	●	●	●	A B C	High
7	None	None	CAD Consultant	$50 Million	Consultant Office								Moderate

(1) HO = Home Office, PS = Project Site

(2) A = Hired Trained CAD Operators, B = Providedd Training Materials, C = Vendor Training Provided

Another company uses AutoCAD on a IBM PC compatible, 386-based computer, connected to a pen plotter, at one of its project site and has an equivalent setup in their home office. Although the company has a home office engineer trained to use CAD, this engineer only advises and supports the project site in its use of CAD. The project manager has had to rely on a series of inexperienced CAD operators to produce construction drawings. None of the project management personnel have any experience managing or operating CAD systems and they do not understand or exploit the capabilities of their CAD system. They require only standard construction drawings and have been extremely frustrated getting drawings prepared efficiently and on time. They have automated their drafting and in the process lost control of it. CAD was implemented on this project at the direction of a higher manager, but no one on site really understood CAD or its potential to improve their work. The project was not designed using CAD so they were not able to get CAD files from the A/E.

Another company used an IBM PC compatible, 286-based computer supported by a pen plotter. Originally, they operated the system from their home office, but they moved it to the field after construction began. Two computer-oriented engineers, one of whom wrote several important interface programs to support their intended applications, supervised the CAD operator. While the CAD system supported their operations well, they were frustrated at the bottleneck created by their pen plotter, which took fifteen to thirty minutes to plot a standard drawing. After they moved the system to their project site, they stopped updating their drawing files with small changes because it took too long to plot the new drawings. By the time they finished, the drawing files did not reflect many important changes.

Another company used VersaCAD on a single Apple Macintosh SE 030 computer with a variety of graphics and storage peripherals and a standard laser printer for output. All of the hardware belonged to one of the project engineers who brought it to the project site to support his own work; the company provided only the CAD software. The project engineer who operated the system was an architect-turned-constructor who had prior experience as a CAD consultant. He used many of VersaCAD's advanced capabilities including building CAD libraries. He also automated other parts of his work using spreadsheets. He plotted files on standard 8.5" x 11" paper and combined them on the office copier to provide his own standard 11" x 17" construction drawings; he used a local plotting service for large plot sizes. This project engineer produced both standard construction drawings and unconventional output to support construction efforts. No other engineers on the the project learned the system and the company has not invested in hardware, so when the project engineer was transferred to another project, he took his system with him. The project engineer was not able to get designs electronically because the project was not designed using CAD.

A fifth company used two IBM PC compatible computers, one 286-based and the other 386-based, running two different releases of AutoCAD in a stand alone mode. One system has a special graphics controller card that only works with AutoCAD release 9; this caused problems upgrading the system. They had an electrostatic printer for output. The project manager and his two assistants were familiar with CAD and its potential but they were not proficient enough to operate it efficiently. Both operators are engineers who learned CAD their first few weeks on the job from manuals and on-line tutorials. They began using CAD to prepare standard construction drawings, and they have expanded their use to take advantage of many of he capabilities of their systems. CAD helps them identify and resolve discrepancies in the contract drawings as they prepare construction drawings. The lack of CAD operating procedures restricted use of the CAD systems to the two main operators. This company did not receive the designs electronically because the project was only partially designed using CAD.

Another company, a general building contractor, employed a CAD consultant rather than buying and operating their own system. The consultant used an Intergraph system and provided only 2D output to the project. The company relied on the consultant for guidance in formatting and specifying necessary output. The company subcontracted most of its work but they had the CAD consultant provide customized background drawings for each of their subcontractors. Previously, they would have just forwarded copies of the contract documents to the subcontractors. None of the company's project personnel knows anything about CAD and despite the benefits they believe they have received from CAD, they are not interested in owning or operating a system. They did not receive any of the contract documents electronically.

A final construction-only company has eight IBM PC compatible, 386-based computers running Intergraph Microstation while several workstations also maintain AutoCAD capability. All computers are networked to a Sun Sparcstation with a high capacity storage device, which provides networked file access and peripheral support including an electrostatic printer. Five of the operators are junior project engineers; three are temporary hires from a local CAD service bureau, brought in to help during a peak production period. The company originally acquired CAD to prepare standard construction drawings but their use has expanded to take advantage of many of the advanced modeling and programming capabilities of the systems. Initially, they had a dedicated system administrator who set up the system and established procedures. This administrator left the project and now several of the advanced operators with prior system experience share system administration responsibilities. None of the senior project management personnel or company managers are trained to use CAD but several of them understand CAD's capabilities and routinely request innovative applications. This company received all of the contract documents electronically, however, they found that the A/E did not use CAD properly, so the CAD files are of little value to them.

Finally, two large EPC contractors have had varying success trying to implement their advanced CAD systems on project sites. One of these contractors placed a workstation with access to home office design files on a project site. They proved that the project site could be physically linked to the network but they did not use the system productively. The second contractor could not find a project manager who wanted and was willing to pay for an advanced modeling system on their project. This company now has plans to place an advanced workstation with 3D modeling software on an upcoming project but despite their advanced design capabilities, their project sites operate outside the integrated environment. Both of these companies are attempting to implement CAD on the work sites for design/construct projects. All data transfers to the construction forces will be internal and should occur without significant resistance.

Characteristics of Success

Based on the variety of systems exhibited by these companies and their varying levels of success using their systems, the researchers identified several characteristics that made some companies more successful than others in using CAD to support their construction operations. The successful companies had engineers operating advanced systems and using advanced capabilities of their systems. These companies were committed to making CAD support their construction activities regardless of where they physically placed the workstations.

Engineer Operators

The companies that used engineers to operate their CAD systems benefited more than those that used CAD operators. While few of the engineers interviewed during this research received any formal training on their CAD systems, they were able to learn quickly. Engineer CAD operators combined knowledge about the construction operations, which their drawings must support, with an understanding of the system used to produce those drawings. This combination allowed them to use capabilities of the system to provide the most useful information for the construction forces. As discussed in Chapter

3, this frequently resulted from using the CAD system to manipulate design information and produce useful but unconventional construction aids.

Commitment

Beyond having engineers operate the CAD system, the engineer operators and their superiors must be committed to the use and success of the CAD systems. The committed engineer operators spent necessary overtime learning the systems and exploring advanced capabilities, which they later began to use. In contrast, on the one project where CAD use was dictated by managers apart from the project, the lack of an active champion was reflected in their ineffective use of their CAD system. Committed superiors are also necessary to support the users with time, hardware and understanding. These committed superiors understand that to be progressive, their engineer operators needed time to explore the software, advanced hardware to run the software properly and encouragement to stay aggressive, innovative and committed to their use CAD. These superiors were committed to CAD because they believed that CAD was a tool that could support their overall project goals.

Advanced Systems

Efficient CAD operations relied on advanced computers and peripherals. Most CAD literature lists the minimum hardware requirements to run the software. The minimum requirements are often far below actual needs to run the software properly. AutoCAD, for example, runs frustratingly slow on 286-based machines. Poor or inconsistent system performance, as found on one project, frustrated the engineer operators and reduced their commitment to using CAD for all of their needs. Additionally, electrostatic plotters or laser printers are necessary. Paper drawings remain the output of CAD work. Pen plotters create frustrating bottlenecks. Therefore some users do not make small but important changes, which destroys the integrity of the CAD files. While many people cite cost as a major issue, companies considering CAD should evaluate only the difference in price between the inadequate low-end and adequate higher-end systems. This researchers have found that the premium paid for advanced systems is more than offset by increases in production and usefulness of the system.

Advanced Applications

The companies that used more of the advanced capabilities of their CAD systems enjoyed greater benefits. Limiting use to produce standard construction drawings limited benefits from their investment. The companies that took advantage of the vast amounts of accurate information their CAD systems stored and manipulated that data using the tremendous computational power of their CAD systems, produced more useful construction information and significantly improved their construction operations. The companies that used advanced capabilities of their systems relied primarily on innovative engineers who operated their systems to exploit those advance capabilities.

CAD On Site Beneficial But Not Critical

Companies that used CAD on their project sites were able to respond to the needs of their construction forces most efficiently, but several companies have been able to support their construction efforts using dedicated home office CAD systems. Several of the managers interviewed during this research indicated that an optimal configuration would probably include construction site CAD systems supported by home office CAD assets during critical periods. Regardless of the actual location of the CAD system, the CAD users must remain focused on supporting construction activities.

Barriers

While the companies investigated have benefited from the configurations of CAD discussed above, they faced many barriers in implementing CAD into their construction operations. These barriers are categorized as organizational barriers, which concern how the companies introduce CAD, technical barriers, which concern the state of the hardware and software, and institutional barriers, which concern how the state of the construction industry affects efforts of constructors to use CAD.

Organizational Barriers

Organizational barriers describe difficulties that individual companies have had in implementing CAD. These barriers concern the company's structure, its policies and its people.

Misconceptions Concerning Productivity

Few of the companies interviewed claim significant increases in drafting productivity because they use CAD. While many of the people interviewed thought they would increase drafting productivity five to ten fold, none of them now believe that improving drafting productivity is the major benefit of CAD. Where there is repetition in the drawing or where the CAD user can take advantage of previously stored symbols or components, productivity may be slightly improved. Most of the applications of CAD on construction sites, though, require the CAD user to review contract documents to find all information that must be included on a new drawing. CAD does not improve the research time (and probably will not until contractors get appropriately layered contract documents electronically from the designers), so the initial drafting effort remains relatively unchanged.

Lack of Trained People

All of the companies interviewed cited the lack of trained CAD operators as a major barrier to their CAD operations. This is both an organizational and institutional barrier. All companies are affected and each must deal with the shortage in their own way. Given the lack of trained CAD personnel throughout the industry, companies that implement must decide whether to train CAD operators to support field engineering or to train engineers to use CAD. Both choices present additional dilemmas.

Several companies decided to hire people trained to use CAD and then teach them what they needed to know to support the construction operations. One project manager complained that while his CAD operators were well trained, they prepared all drawings as if they were contract documents, which are too general and fragmented for the field crews to use effectively. They had trouble teaching the CAD operators that construction drawings must be comprehensive and focused on the particular tasks to be performed. Another firm relied on one experienced CAD operator to do all of their CAD work. When that person left, the company's CAD efforts stopped. Other companies that have hired inexperienced CAD operators find managing those people during their learning phase difficult. The managers know what drawings or plans they want but frequently they are unable to assist the CAD operator to achieve the desired output because they are not familiar with CAD. Compounding these problem, pay scales for CAD operators are relatively low, so even experienced CAD operators move around frequently.

Several of the companies interviewed trained engineers to operate their CAD systems. Project managers speculate that this may create a problem insuring that the engineer does not operate CAD too long and still rotates to other important engineering positions. The incentive to leave the engineers with the CAD is strong. Most engineers admit that it takes several months with any CAD system to become proficient and even longer to gain experience modifying and customizing the system. On one project, engineers were hired with the understanding that they would operate CAD for one year and then rotate to other positions. Looking forward the project management says this will happen, however, given the stress and immediacy of most construction projects, it will be interesting to see if the company is willing to replace the experience operators with new operators who will not be able to maintain the same level of production.

Lack of Time to Experiment and Learn Systems

The CAD users interviewed were extremely busy and had little time to learn or experiment with their systems. Most of the CAD operators knew only basic operations of the CAD and they still needed training to refine their skills on the job. Most of the engineers had no formal CAD training at all prior to the assignments using CAD. Their companies provided books and relied on a short period with CAD tutorials to make them proficient. On projects where CAD was used effectively, the engineers who used CAD explored its capabilities in their free time and spent many extra hours learning new skills. The company, though, had no plans for developing skills they need.

Inability of Construction People to Exploit CAD

Several companies felt that they could use CAD more effectively if their project managers and engineers understood CAD's capabilities and knew what to ask for from the design section. The project managers in the companies that employed CAD operators did not understand the real benefits of CAD and consequently they could not fully exploit its power. These companies need people who understand both the means and the end of the design and drafting process to fully exploit CAD.

Other companies shared the opinion that the construction environment is already a very dynamic environment and project managers do not need more assets that require intense supervision. One project manager found that CAD distracted many of his project engineers from supervising construction. They spent too much time in the project trailer explaining their requirements to the CAD operators who had no construction experience. This project manager felt that CAD introduced unknown capabilities that they were untrained to exploit.

Lack of Champions

Another major problem for the use of CAD in construction is a lack of champions. This research did not detect any industry-wide discussion that would encourage innovative individuals to apply CAD in construction. Further, even in the companies interviewed that are using CAD, for each person interviewed who sees benefit in their use of CAD, others see little benefit or are not interested in using CAD. In one company, a single engineer championed CAD on his projects. After eight months on one project, he was transferred; none of the other project engineers on his first project had expressed interest in using CAD, so that project lost a valuable asset.

In another company, an upper level manager directed the project manager to use CAD at the project site. The project manager supported their use of CAD but he was never committed to its success. He remained consumed with other project management issues and did not push CAD. None of the project's engineers learned CAD so their progress is limited to the gains they make with CAD operators (operators they have difficulty keeping).

In one large EPC company, the CAD department manager saw tremendous benefit to using CAD on site and tried to convince project managers to use it. Unfortunately, he was unable to find a project manager who was willing to take the risk and try to use CAD on their project.

Many "construction people" have not even considered using CAD in their work and don't know what to ask for in the way of CAD support. They just keep plodding along doing things the same old way despite the increasing availability of potentially beneficial technology. These people need to be led by champions to see the value that CAD can offer construction.

Lack of Corporate Plans

While the large EPC companies had strategies to exploit their advanced modeling capabilities, only one general construction company had a company strategy that identified their use of CAD as a strategic asset. This company's strategy considered CAD primarily for its marketing value and did not fully considered the advantages that CAD offered in their construction operations. Most of the companies interviewed bought CAD without any plans for what they expected from it, but with many misconceptions about what it could do for them. Without appropriate consideration, these companies could not adequately determine whether or not CAD served their general business interests.

Philosophy Concerning Construction Overhead

Several of the companies also found that construction site use of CAD conflicted with their project and company financial management policies. While most of the companies routinely charged computer assets to project overhead, the introduction of CAD significantly increased automation expenses. Project managers who wanted to keep their project overhead low naturally balked at the additional expense on the project. One project manager contends that construction people try to keep very tight control on project overhead and he views additional supervision for the CAD as an unnecessary addition to project overhead. This project manager was also concerned that they would not be able to keep their CAD sections fully employed throughout the duration of the project. Consequently, he had to pay for an asset he could not fully employ.

Systems Administration

Administering a CAD system requires skills not normally found in a construction company. Most of the companies interviewed relied on in-house people to administer their systems, which in most cases resulted in inefficient CAD operations. In most of the companies, the person responsible for the systems had very limited experience with the

CAD systems and even less knowledge about the hardware. In one company the two CAD users administered the system but they were so busy that they did not have time to resolve difficulties in upgrading. After a brief attempt to update their software, they reverted to old software to maintain production.

Another company hired a system administrator who was instrumental in establishing a network, setting up a filing system, and helping operators learn their system. This position was new to the construction site and increased overhead without contributing directly to their construction or project administration efforts. A person who can manage the hardware, establish and enforce standards, maintain libraries and help operators resolve problems can significantly improve the overall CAD operation.

Technical Barriers

Few technical barriers affect the companies interviewed. The technology exists to solve most of the technical problems experienced in the companies studied, unfortunately, the money was not always available to buy necessary additions. Some of the frustrating but solvable technical problems include:

System Requirements

CAD software advertisements frequently underestimate the hardware requirements for their software. While such advertisements may be generally correct, even the most basic CAD systems need advanced hardware to run well. All companies interviewed have upgraded their CAD systems to 386 or equivalent -based systems operating at 33 Mhz. Most CAD systems runs frustratingly slow when less advanced hardware is used. The companies interviewed have spent between $15,000 an $20,000 per workstation. CAD is still not just another piece of software to install and use on most currently available hardware.

Plotting

Most companies cited plotting as a major bottleneck that adversely affected their use of CAD. Although printer prices are falling rapidly, they are still relatively expensive and many companies have not justified the additional investment for fast electrostatic printers. One company spent over 60 days to plot over 600 concrete lift drawings with their pen plotter; even a simple plot can take 30 minutes or more on a pen plotter. The person interviewed indicated that this bottleneck prevented them from using CAD to correct drawings on site. If changes were required, they made the changes manually. Consequently, the CAD files were never updated and it was difficult to determine what plans were the most current.

Another company that invested in an electrostatic printer found that it needed to be managed closely too. They began by simply plotting the total number of prints required on the electrostatic printer. This caused delays in printing different plans from different workstations. They solved the problem by buying a large size copier capable of copying blueprints. Now, they only plot one original and then make all required copies on the copier.

Still another company had no plotter at all. They relied on a standard laser printer. For most of their drawings they used 8.5"x11" paper and combined halves of drawings by copying them onto a single 11"x17" sheet, a format they found very convenient. This filled most of their needs. When they needed full sized plots, they sent their plot files to a CAD bureau via modem and then picked up the prints at the CAD bureau's printing office.

Institutional Barriers

Institutional barriers do not affect how companies currently use CAD on their project sites, but the lack of integration and the lack of electronic data transfer reduces the efficiency of construction site applications of CAD. The companies investigated cited the following institutional barriers to their efforts to use CAD more effectively on their projects.

Owners Not Involved in Integration

One project manager believes quite emphatically that they will not be able to use CAD effectively on their projects until owners start requiring A/E's to use CAD and to pass their design information on to the contractors electronically. Members of CIFE, the organization sponsoring this research, appear to generally agree with this notion and believe that the construction industry, architects, engineers and contractors, need to educate owners about the benefits of integration on individual projects. Once owners force integration, all project participants will benefit.

Fragmentation of Construction Industry

The tremendous fragmentation of the construction industry also inhibits the use of CAD. For complete integration and transfer of designs electronically, many levels of contractors, subcontractors and suppliers will have to bear the overhead burden of CAD. On many commercial building projects, no single contractor constructs a major portion the project so the gains for any individual company are limited. Heavy civil contractors, who perform most of their work with their own forces, have found the most applications of CAD because they retain the benefits of their investments.

Many Designers Don't Use CAD

Several project managers insist that most A/E's and design consultants do not complete their designs on CAD. One project manager believes that most A/E's do 50-70% of their designs on CAD and then, usually because of time pressures, make changes to the plans manually. By the time the A/E prepares the final contract documents, the CAD files are outdated. Contractors will not benefit from electronic transfers of data until A/E's use CAD for their entire design process.

Difference of Environment Between Design and Construction for CAD Operator

Two companies had difficulties keeping good CAD operators because the CAD operators could not cope in the dynamic and often stressful construction environment. On one of the projects, the CAD manager had been trained in a calm, and structured design office and did not like working in the faster paced, rapidly changing construction environment. On another project, the CAD operator resented constant interruptions from the construction people who either needed different information or, when the project required, wanted him to do non-CAD work. This CAD operator was further frustrated because the project managers were unfamiliar with CAD and could not keep him busy, which made him available for other duties. These CAD operators were trained in a design environment and were used to clear job focus. The needs of the construction project must come first but keeping motivated and trained CAD operators is also essential to using CAD effectively to support construction.

Few Consider Using CAD in Construction

A final institutional barrier the researchers inferred from the findings is that the total lack of discussion concerning the use of CAD in construction has prevented more people from trying it. Several of the companies interviewed responded defensively because they felt that their applications of CAD were basic or that they were behind others in the industry. Actually, these companies were the most progressive and innovative. Further, most of the literature concerning CAD focuses on state of the art systems, which are not relevant to construction firms. Most construction firms will only implement proven technology or technologies that someone within the organization is confident will benefit the company. With so little in the literature, there is nothing to prompt "technological followers" to use CAD in their construction efforts.

A Framework for Cost Analysis

In order to enjoy any of the potential benefits of CAD on a construction site, constructors must first overcome several barriers, one of which is their inability to quantify the benefits they will realize from their investment in CAD. Many companies originally bought CAD because they believed it would increase their drafting productivity substantially. While these firms have generally experienced modest productivity increases, in many cases the savings from these improvements have not offset the cost of the systems. Most of these firms now value other benefits of CAD, but they still seek economic justification for their investments.

The following framework should assist construction firms in justifying investment in CAD to support their construction operations by offsetting the additional costs of automated design or drafting with operational savings. The framework reduces the analysis from a relatively abstract company or project level to a more concrete crew-hour level and requires the constructor to make subjective estimates of the potential improvements for specific activities. Although in some applications materials savings could also be significant, the framework considers only labor savings because labor represents the single largest variable cost on construction projects.

The Framework

Calculate System Cost

- This should include accurate hardware and software costs and estimates of training costs, lost productivity during learning periods and maintenance.

Consider Increased Operator Costs

- Most CAD operators displace manual drafters so they do not represent an increase in cost of the automated system over manual procedures and should not be included in the increased cost estimate. CAD operators hired in addition to manual drafters should be considered.
- If an engineer using CAD replaces a manual drafter, only the incremental difference in wages and benefits should be included. If the engineer would otherwise have drafted his own plans then there is no increase in cost.
- The cost of employing a dedicated systems administrator should be included. If system administration is just someone's additional duty, however, no increase in cost should be considered because he will still focus on his primary duties (although he may have to work extra hours). Overtime caused by system administration responsibilities should be added.

Average Construction Crew Size

- They average construction crew size can be determined easily from manning reports and project schedules. This should include foremen and craft personnel only.

CAD system to Crew ratio

- Dividing the average crew size by the number of CAD stations on site indicates how many craft personnel each CAD system supports.

CAD Cost/hour versus Crew Cost/hour

- Both CAD cost and crew costs can be broken down to an hourly rate for consistent comparison.
- The total cost of the CAD system should be divided by the expected useful life of the system, probably in the range of three to five years. Each year should be further divided into 2080 work hours. This should be conservative because the CAD systems on several of the projects investigated during this research were used more than 8 hours per day.
- Crew costs per hour should include the hourly wages and burden for the number of craft personnel that a single CAD system supports. If one CAD system supports 20 craftsmen who earn $25.00 per hour and the burden is $10.00, the crew cost would be 20x$35 or $700/hour.
- When a crew uses equipment that is usually billed by the hour, the cost of that equipment should also be added to the crew cost per hour.

Breakeven Analysis

- The breakeven point is the number of hours the CAD system must operate to save one crew hour. If a CAD system costs $10.00 per hour to operate (a reasonable figure as will be shown), and crews cost the project $700 per hour, if the work accomplished using the CAD in 70 hours saves one crew hour, the CAD pays for itself.

Quantitative Assessment of Time Savings

- The subjective or qualitative part of the framework requires the constructor, who knows how his crews normally operate, to assess how time could be saved. Chapter 3 discussed many different ways in which various constructors have used CAD to provide better, clearer, and more current information to the construction crews. An experienced construction manager or project engineer knows how often his crews stop for clarification, move because of changes or errors, wait for layout of complex configurations, double handle materials or adjust component locations from approximate first guess to final positions. These inefficiencies and many more offer tremendous potential for saving construction crew time due to the use of CAD in preparing the construction drawings.

Fallacies

Several fallacies creep into the framework and must be exposed early.

- A CAD operator or engineer would not spend 70 hours on a single construction drawing sequence. Consequently, many of the savings may be either accumulated over several construction tasks by several smaller crews or the savings may be more pronounced than predicted.
- Many of the savings come from the elimination of errors that contractors did not plan to make. Realistic contractors acknowledge that errors do occur and focus much of their efforts on limiting them. CAD is a tool that can help them do just that.
- Not all applications of CAD will save crew time, but if only a few do they alone can justify CAD economically.

Highlights

It is important to highlight again that without CAD a drafter or an engineer would have to prepare construction drawings manually. When the cost of construction crews may exceed $700 per hour, it should not be difficult to justify an additional $10 per hour to support them if that tool has the potential to save crew time. As the examples in the previous chapter showed, CAD offers the potential to save construction labor. Therefore, the potential return on this investment can be substantial.

A Real World Example

One contractor constructing a $180 million waste water treatment plant jokingly referred to their use of CAD as a $100,000 experiment. In addition to the system acquisition costs, they later decided that they needed a system administrator. Other unanticipated expenses have raised their system costs close to $200,000.

Two of the assistant project managers believe they will recover their expenses. Discounting any salvage value of the system, CAD hardware and software will cost the project approximately $200,000 for the eight workstations that they now have. The average cost per workstation was $25,000, or $6250 per year for the 4 year project, or $24.00 per day (assuming 260 workdays per year) or $3.00 per hour (for an 8 hour day). The cost for each of the engineers who operates a CAD workstation is approximately $50,000 per year, combined wages and burden. They would otherwise have prepared shop drawings manually, so this is not an incremental cost. Therefore, a CAD hour costs $3.00.

The project currently employs approximately 300 craft personnel. The numbers and types of craft personnel will vary during the project, but they will always far exceed the number of workstations. Assuming that they normally have 7 workstations operational at one time, based on the 300 man crew on the project, each CAD engineer must produce plans to support approximately 40 craftsmen. Carpenters cost the project approximately $40.00 per hour wages and burden, so the crew cost for 40 carpenters is $1600.00 per hour.

Therefore, the cost of the relatively inexpensive workstation used to create better, clearer, more accurate or more current data, which saves the crafts time or prevents rework, is quickly offset by labor savings to the project. Hypothetically, if the CAD engineer/detailer spent an entire week preparing plans that only saved the 40 man crew one hour, the project would still save money ($120.00 per week versus $1600.00 per hour).

Estimates of Possible Savings

The contractor used CAD to produce a new overlay for an aerial photograph which helped them plan a clearing an grubbing operation. Without this overlay, they would have had to send a survey crew to designate trees to be removed. Assuming that a three man survey crew (surveyors generally cost about $50.00 per hour) would have taken two hours to accomplish their survey, this application of CAD saved 6 man hours. The CAD was used just to replot a site drawing at a new scale so the CAD time involved was only about fifteen minutes. $0.75 of CAD costs saved $300.00 of crew costs.

This contractor also used CAD to plan their concrete forming operations. Their plans included specific locations for the placement of large gang forms which require cranes for movement. Rather than moving the gang forms into their approximate position first and then positioning them precisely, they now place them specifically the first time because the construction drawings prepared using CAD give coordinates for the exact placement of all forms. Assuming that the standard crew for moving and placing these forms would be five men and a crane, and that handling the forms only once saves 30 minutes, the crew savings would be 2.5 man-hours or $100.00. The project engineer used the CAD for 2 hours to prepare the detailed formwork drawings which cost $6.00.

This contractor resolved a conflict between a continuous footing and a separate footing in the foundation design and eliminated a field delay. This saved the 10 man forming crew 30 minutes (and possible rework later) for a total savings of 5 man-hours or $200.00. The foundation drawings required 3 CAD hours which cost $9.00.

In another instance, an inspector stopped a work crew because their work did not match his set of plans. The foreman quickly determined that his plans were current and their work was correct; the inspector's plans were outdated. Without such current information, the six man crew could easily have lost an hour getting the correct information and making necessary changes. In this case, CAD saved the project six man-hours at $40.00/hour or $240.00.

All of these are estimates. It is hard to determine how long it would take a survey crew to perform a task, how much time is save by only handling forms once or how long a crew would wait for information to clarify a construction problem. These estimates appear reasonable and highlight how CAD can save significant construction labor costs. Further, these are just a few examples that show how savings on just some applications will offset the cost of using CAD on other work that produces no labor savings.

Despite such favorable numbers, cost is a barrier to the use of CAD because at the budgeting level, CAD appears as a constant expense with no direct savings to offset the expense. These calculations reflect and attempt to quantify unseen benefits. As the numbers show, though, they don't need to save much time relative to their initial plan to justify the investment. Two large design/construct firms indicated that they used to plan for 3-5% for rework on major industrial projects. On this $180 million project such a range represents $5.4 to $9 million. Viewed another way, they only have to reduce errors and rework 0.1% of the total project cost to make their investment payoff. As discussed throughout this report, even 2D CAD offers the potential to achieve this level of savings and possibly much more.

This chapter analyzed how several construction companies implemented CAD to determine characteristics of success and barriers to the implementation of CAD in construction. A framework for cost analysis of CAD was also presented to help companies compare the cost of their CAD systems with the potential construction savings from using CAD in field engineering functions.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

CAD can improve field engineering and construction operations now. The findings presented in the previous three chapters support conclusions regarding applications of CAD in construction, implementation of CAD on construction sites and barriers to using CAD in construction. This chapter discusses these conclusions and makes recommendations for implementing and using CAD to support construction operations. An assessment of accomplishments regarding the research objectives and recommendations for further research are also included.

Conclusions Regarding CAD Applications in Construction

2D CAD can be used to support construction effectively now. 2D CAD enhances the constructor's execution of a variety field engineering tasks generally. Most construction companies begin using CAD to produce standard construction drawings. Those with innovative engineers and operators soon learn that 2D CAD enables them to perform standard operations better and to create new, beneficial construction information. The constructor's ability to take advantage of this new tool is limited only by the needs of their project and the imagination and skills of their people.

Constructors can exploit several important capabilities of 2D CAD systems to support their construction operations. These include:

- the ability to copy and reuse drawings to make their design and drafting efforts more efficient, more consistent and less error prone;
- the ability to make changes easily to accommodate design modifications and additions, to correct design errors, to accommodate as-built conditions and to insure that field crews have accurate and current information;
- the ability to present design information clearly and consistently to avoid misinterpretations and confusion in the field;
- the ability to layer information for efficient viewing and plotting;
- the ability to represent objects at full size, which establishes accurate spatial relationships between objects and assists in detecting interferences between objects;
- the ability to plot complex shapes and give accurate dimensions for construction layout;

- the ability to plot drawings in most appropriate format ranging from standard drawings to details extracted on 8.5"x11" sheets;
- the ability to access automatically generated geometric information about objects to bridge the gap between drafting and design;
- the ability to customize the system to support routine or complex operations, such as maintaining symbols libraries, calculating survey control points or integrating materials lists for design reference;
- the ability to market the company as a technically advanced constructor;
- improving overall communication of construction information.

Constructors who understand these capabilities of CAD can envision new, innovative ways to approach their field engineering activities.

3D modeling systems provide tremendous additional power and capability to the constructor beyond 2D CAD systems. 3D modeling systems reduce projects schedules, decrease field rework and improve materials control. These benefits result from using the 3D modeling systems in the design phase, regardless of whether or not the constructor uses CAD. More advanced systems also allow constructors to plan and simulate construction activities and integrate other project control systems based on the design model. Unfortunately, these systems are new, in most cases still experimental, and extremely complex. Advanced 3D modeling systems provide a hub around which projects can be completely integrated. Several EPC firms benefit from 3D modeling but its effect throughout the construction industry is very limited.

3D modeling systems specifically support construction operations by allowing:

- 3D visualization of different perspectives;
- dynamic simulation of construction operations;
- batch materials take offs for accurate materials quantities.

Currently, general contractors make only minimal use of 3D models to visualize configurations on projects. Cost, time and complexity prevent most constructors from using 3D models on site despite the potential benefits.

Conclusions Regarding CAD Implementation on Construction Sites

Companies that currently use CAD effectively in their construction operations share several characteristics.

- They rely primarily on engineers rather than former drafters to operate their systems.
- They use relatively advanced computers and peripherals.

- They take advantage of advanced capabilities of their CAD systems to leverage their design and drafting efforts.
- They are committed to using CAD because they understand its capabilities and how those capabilities can support their construction operations.
- They focus on construction/field engineering tasks whether located in the field or in the home office and do not get distracted with other non-construction oriented applications.

Findings and Conclusions from Survey

Significant Findings from Survey

The analysis yielded many findings concerning how US and Japanese companies use computers and CAD in construction and the difference in attitudes and applications between the two countries. Although the survey was not designed to compare US and Japanese construction companies, some interesting findings in this area arise.

- US construction companies use computers for more different applications than Japanese companies but Japanese construction companies use CAD more than US construction companies.
- More civil contractors use CAD than building or industrial contractors in USA.
- Small US companies report having higher percentages of people who are very competent using computers. Perhaps this is because smaller companies use computers more to leverage the skills of the people the have.
- One fourth of medium and small US construction companies have no interest in using CAD.
- Civil contractors report the lowest portion of projects designed using CAD but they still use CAD the most in their work.
- Few participants think that preparing shop drawings manually is efficient, regardless of whether or not they use CAD or prepare shop drawings.
- Most Japanese construction companies have used CAD to prepare shop drawings.
- Large companies see more potential for CAD in construction than small or medium companies.
- More Japanese companies think than CAD benefits construction than US companies.
- Perceptions of barriers vary greatly by size of company.
- Large companies don't think that price is a major problem.

- Larger companies believe that resistance to change is more of a problem than small companies.
- In the US, the companies that use CAD are not bothered by potential barriers as much as the companies that use CAD. (The perception of problems has changed as they use CAD.)

Conclusions from Survey

Based on these general findings, the researchers have formulated several conclusions:

- The high response rate indicates great interest in this area.
- Many construction companies see great potential for CAD to improve their field operations but they are struggling to implement it.
- Some differences exist between US and Japanese construction industries but both are struggling to implement CAD into their construction operations.
- Computers are an integral part of construction management tools
- Companies throughout the industry have experienced the same problems that the researchers found in the interviews.

Conclusions Regarding Barriers to Use of CAD in Construction

Technology is not a barrier to the use CAD in construction. Current technology can be used effectively to support field engineering and construction. The primary obstacles lay in the organizational characteristics of specific companies (organizational barriers) and the general nature of the construction industry (institutional barriers).

Organizational barriers include:

- a lack of people trained to use CAD;
- a lack of appropriate internal and external training programs for available personnel;
- too little time for operators to experiment and learn advanced capabilities of CAD systems;
- a lack of champions committed to making CAD succeed on construction sites;
- a lack of corporate plans that consider CAD as a strategic tool;
- a lack of experience by project managers and engineers to manage a new unfamiliar tool in an already demanding and dynamic environment;
- reluctance to accept expensive CAD systems in overhead;
- inadequate hardware to run software efficiently and produce output quickly;

- insufficient systems administration efforts to establish procedures, maintain hardware, train people and customize systems.

Institutional barriers include:

- industry fragmentation;
- a lack of owner involvement;
- designers not using CAD universally or completely;
- a different working environment for CAD operators;
- a general lack of consideration for using CAD in construction;
- research focused on design integration with little consideration of how constructors fit in an integrated project environment or benefit from CAD.

Conclusions Regarding Project Integration

Project integration remains an elusive goal. Although CAD systems are widely used by architects and engineers, many still design manually. Frequently A/E's who use CAD do not complete their designs on CAD, so electronic files are outdated when construction begins.

Few constructors currently use CAD. While this research found several innovative construction companies, the use of CAD by construction companies is still unusual. Those who do use CAD generally acquired it as a drafting aid while only a few have advanced to more powerful applications. In either case, these companies have had to duplicate design data using CAD before they could take advantage of CAD's capabilities.

Two distinct forces within the construction industry are beginning to encourage project integration. Unfortunately, these trends will not converge soon. Several large EPC contractors are developing advanced applications based on their design models to integrate design and construction. Smaller general contractors are using CAD to support their construction efforts and are beginning to understand how they would benefit in an integrated construction environment. The EPC contractors are integrating projects internally, while most contractors must integrate a process in which they just one participant. The desire for project integration is growing, but the end is not yet in sight.

Recommendations for Construction Site Application of CAD

There is no recipe for using CAD successfully on construction sites. Each company is different and must consider for itself how it should introduce and use CAD. The researchers have identified four general phases of CAD implementation: planning, implementing, managing and interfacing with external organizations. Constructors that want to implement CAD should consider several issues within each of these different phases.

Planning

Understand the Capabilities of CAD

Before any company implements CAD, it must understand what CAD can and cannot do for them. They need to understand the difference between 2D CAD and 3D modeling and the capabilities each technology offers. Most companies will find that increases in drafting productivity will be slight but other benefits will be valuable.

Cultivate Champions

Champions are essential to introducing any change into an organization. Construction companies considering CAD must find or cultivate champions who will work to make CAD support their construction efforts. Making CAD succeed in a construction environment requires the commitment to break with tradition, explore potential applications and persist. Without a committed champion, implementation could be easily blocked by numerous barriers. Champions overcome barriers.

Getting Started

Buy Appropriate Systems

Companies implementing CAD should buy appropriate systems. CAD systems are not a good place to save money. Less expensive software may lack features that make CAD useful and efficient. Managers who understand CAD can select an economical software package that has the features they need. CAD software needs advanced hardware to operate efficiently. Hardware based on slow processors makes operating CAD software frustrating and inefficient. Electrostatic plotters or postscript printers are also essential. Cheaper pen plotters are slow, and problems with pens and paper frequently slow and frustrate users. The cost of electrostatic plotters is falling and the premium paid for one is more than offset by the increased efficiency of the system as a whole.

Train Engineers

Given the general lack of trained CAD operators, most companies train their own; they should train their engineers. CAD can help project engineers perform field engineering responsibilities more efficiently. Dedicated CAD operators, on the other hand, operate between the engineer and the required plans -- not a desirable approach. Engineers also tend to be more innovative using CAD because they know what information the crews require and experiment with the systems to find the best way to create and present it. For maximum efficiency, the engineers should use the CAD constantly for six months to one year and then rotate to other project management positions. They should not be captive to the CAD system but their skills must be developed and used.

Training should consist of three phases: formal training, on-the-job training and experimentation. First, a formal training period is essential to teaching efficient CAD skills. Pushing engineers into production drafting too early limits their understanding of the system and their potential to innovate with the it. Following formal training, the engineer can learn on the job using comprehensive supplemental materials. This also provides references for answers to questions about the system. Finally, the engineers needs time to experiment with CAD and learn advanced capabilities. Advanced features of CAD systems can significantly leverage a designers abilities, therefore this is time well spent.

Train Managers

Managers need to know how CAD should be used and what they can expect from it. This knowledge is essential to allow managing CAD as just another tool. Managers also need to know what CAD cannot do; they should not be mislead to expect tremendous improvements in drafting productivity and they need to know that producing a drawing takes more than just pushing a button.

Establish CAD Operating Procedures

CAD operating procedures are essential to efficient CAD use. Procedures should address file naming conventions, layering conventions, network procedures, symbols library construction and use, plotting conventions and any customized features of the system. Procedures should be dynamic and include improvements as they are made. Standard procedures allow operators to learn the system quicker and more easily and prevent design data from becoming hostage to one user.

Administer the System

CAD systems require knowledgeable administrators. Isolated CAD systems can be complex; networked CAD systems increase complexity significantly and will probably exceed the ability of most construction site "hackers" to administer. Large investments in CAD justify additional expenditures to insure that the systems operates properly. Technology changes the skill mix of most working groups, construction is no exception. Construction people must accept that the cost of the benefits they receive from CAD may have to include a CAD administrator.

Identify Good Starting Activities

Companies should start with basic construction drawings that they would otherwise draft manually. Good candidate tasks are concrete form or lift drawings, piping isometric drawings or equipment layout drawings. After gaining experience in routine tasks they will have better skills to perform more complex tasks.

Progressing

Explore Advanced Capabilities of CAD

After developing basic skills using CAD, the engineers operating the CAD systems should explore more advanced capabilities such as parametric design functions, macro programs for complex functions or elementary 3D modeling. These advanced capabilities leverage the engineer's efforts and in many cases allow him to perform functions or create new unconventional construction information.

Balance Load

Companies implementing CAD on construction sites should also consider placing some systems in their home office to support multiple projects. This setup allows project managers to have only as many systems on site as they can fully employ throughout the project and gives access to additional capability during busy periods. It also enables the home office to perform other design work on CAD and/or use those systems for training and system development.

Evaluate Progress

A natural part of management is to evaluate progress using different tools. CAD should be reviewed critically to determine which activities best support construction operations. CAD is a very powerful tool, but that power can be misdirected. Critical reviews can help keep the use of CAD focused on productive applications.

Disseminate Lessons Learned

Companies that use CAD need to publicize internally what they are doing with CAD. In many cases, CAD begins on a single project. By disseminating lessons learned using CAD, they may encourage others to use CAD. If CAD is used on several projects, internal company discussion may keep different projects from making similar mistakes, or pass on useful procedures. Internal discussion of CAD use can add synergy to the implementation process.

Stay Informed About Technology

Construction companies need to stay informed about technology. Both hardware and software technologies are evolving rapidly. Managers who don't think that CAD is a good investment for their firm now should periodically reevaluate their position based on advances in technology. Companies that use CAD may find enhancements they can add or ready themselves for future changes they will have to make. One way to do this is to subscribe to periodicals such as BYTE, CADVANCE, CADalyst, MicroCAD News or other computer oriented publications, another is to sent representatives to computer trade shows.

Interfacing with External Organizations

Request Electronic Design Files

Companies that use CAD should request electronic design files from A/E's. Most of the work currently done with CAD on construction sites requires the constructor to duplicate design data. Getting information electronically would significantly improve their CAD operations. Constructors should accept disclaimers on the data files if necessary. Even if the paper drawings remain the contract documents, the constructor benefits by not having to duplicate design information. They should compare the electronic files to the paper drawings to determine if the electronic files are current before using them extensively.

Participate with Universities to Develop Engineers with CAD Skills

Constructors should emphasize that the ability to operate a CAD system is a skill that the construction industry needs to develop in active participation with university construction educators. The industry has procrastinated long enough in applying new technologies. CAD helps constructors most when engineers use it. Engineers should come prepared to use CAD and it should be a tool they use in performing their jobs. Developing this capability should begin during the early stages of an engineering curriculum.

A Short Course for Managers

Industry organizations should collaborate with colleges or universities to develop a short course to train project managers and engineers how to exploit CAD. Such a course should focus on many of the issues presented in this report to teach managers how to implement CAD into their operations and what to expect from it.

Information Coordinator

Constructors should initiate a discussion with architects, engineers and owners to develop the role of an information coordinator for construction projects. This information coordinator should consider the project design as information and insure the architects and engineers develop information that supports all project participants, including the constructor. The information coordinator, possibly and owner's representative, an engineer from an A/E firm, a construction manager or even a general contractor brought into the process early, would support the entire project not just one phase of it.

Objectives Reviewed

This section considers the findings and conclusions in light of the original research objectives to see how well the research efforts fulfilled the goals and to identify needs for future research. Each objective is considered separately below.

Assessing Current CAD Use

The first objective of the research was to assess the current applications of CAD in construction. Although the examples were not selected scientifically, they demonstrate the types of applications progressive construction companies are finding for CAD. Since no prior publications discuss any such applications of CAD, this research fills an important void in the published knowledge of how CAD supports construction. It will should also help build better links to include the constructor in an integrated construction process.

Capabilities of CAD

The researchers also defined the capabilities of CAD systems that make its useful in construction. While these capabilities are generally known within the design community, the researchers redefined them in a construction context to help contractors understand how they can benefit from CAD.

Software Improvements

The researchers did not identify any new capabilities required of CAD to make its use in construction more common. They found that there is significant potential for increased use of current CAD systems in construction. Hopefully, results from this research will help convince CAD developers that construction firms are potentially serious CAD users. Therefore, a significant market should exist for CAD tools tailored for construction site applications.

Barriers

The researchers found many barriers to the use of CAD in construction and offered recommendations to overcome those barriers. Many of the barriers are not unique to the construction industry; constructors could have avoided many difficulties by learning from the lessons of other industries. The researchers also presented a framework to help constructors consider the costs and benefits of CAD use in construction to show managers that using CAD to support construction makes sense financially. If this can be done, one of the major barriers will be overcome. This report, by itself, should help remove another barrier, the lack of understanding about CAD and the lack of appreciation for how CAD can support construction operations. This report has explained CAD in the context of construction and it has described many ways in which CAD can improve construction operations.

Needs for Further Research

Since this research was exploratory, it is important to identify areas that require further investigation to guide the efforts of future researchers. Several important needs and questions remain:

- How are CAD designs formatted and presented to best support construction? Do current layering standards such as the AIA Layering Guideline support the needs of constructors? Several constructors complained that designer's layering schemes prevented them from using electronic data transfers; are their complaints justified? How should designers use CAD to support construction applications?
- One major barrier to the use of CAD in building construction is the high degree of subcontracting, which divides the benefits among many participants. The benefits that one subcontractor would realize may not justify the cost of CAD. Researchers should explore the integration issues just within the construction phase of a project to see how the general contractor could best share designs with subcontractors. This could possibly involve a cooperative effort between researchers and constructors to share their knowledge and learn from each other on a real construction project.
- Technology is not the problem in integrating the construction process. Their may be room for improvement in the technology but the main problems of integrating construction projects today are organizational and institutional; these deserve more attention. Perhaps another cooperative project with researchers and constructors would help highlight the issues and suggest corrections.
- Further efforts are needed to incorporate CAD training into engineering curricula. For years, engineers learned drafting because it was the means by which they communicated designs. Much of the AEC Industry uses CAD now so drafting is an antiquated skill that does not merit further consideration. Few efforts have been made to train engineers in the new means of communicating using CAD. Many engineers graduate today not knowing how to draft or use CAD. Engineers in the work force need these skills; the industry needs for them to come with those skills.

- Construction researchers should analyze the area of field engineering. This is a broad area that encompasses many activities. A better understanding of field engineering activities could help constructors understand new ways they can apply CAD and help CAD developers focus on construction operations that need better technological support.

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Key Person Interviewed

Dwight Sale retired from Guy F. Atkinson Construction Company in early 1990 after 35 years of service. During his long career, Mr. Sale performed a wide variety of construction and construction related tasks from managing construction operations, to designing equipment for heavy civil construction projects. His innovative approaches included applications of CAD to support construction. Mr. Sale developed impressive computer skills primarily through personal study and application. He closely followed Atkinson's automation over that past 20 years and wrote many programs to support company projects such as a construction simulation program and a program to analyze truck haul speeds by modeling haul route characteristics and truck engine and transmission performance capabilities. Mr. Sale possesses a unique combination of construction and computer skills.

Applications of CAD in Construction

Formwork Design and Lift Drawings

Guy F. Atkinson recently completed one of the last large civil construction projects in California, the turnkey Calaveras Power Project. This project consisted of a system of dams, tunnels and power houses to complete a hydropower generation network. One of the dams, the McKays Dam, was a double logarithmically curved (top to bottom and side to side) concrete arch dam. Atkinson planned to construct the dam using over 600 separate concrete placements or lifts: each lift was different. They faced a major challenge preparing lift drawings and designing the formwork for each of the 600 different lifts. Mr. Sale, together with his son, also an engineer on the project, and a CAD operator, saw an opportunity to use CAD to simplify their task.

They system they devised combined a program that Mr. Sale wrote in the BASIC programming language and AutoCAD. Mr. Sale obtained the equations that defined the surface of the dam and used his program to calculated and format all the information that AutoCAD needed to draw each of the 600+ concrete lifts. He then exported that information to AutoCAD, which drew the lift drawings for each placement. He could easily add dimensions and offset dimensions for easy construction and quality control. Mr. Sale insists that the system they devised was essential to their success on the project because it was not feasible to produce the lift drawings manually due to the workload and the requirement for accuracy.

Rock Bolt Placement

Atkinson recently constructed a new set of locks at the Bonneville Dam on the Columbia River. The locks, which the Corps of Engineers designed, had to be anchored to the adjoining rock cliffs with over 2000 rock bolts. All that Atkinson received from the Corps of Engineers was a list indicating what type of rock bolt was required at what location. The raw data they received was of little value to the construction crews because it did not relate to any specific concrete placement and it was nongraphical and hard for the crews to interpret. Atkinson personnel plotted the information into a rough 3D CAD model of the locks. This effort yielded several important benefits. First, it related the different rock bolts to different concrete placements so that Atkinson personnel could properly plan the placement of the bolts. Further, the CAD analysis showed that more than 5% of the rock bolts were improperly designed; in many cases, the specified bolts missed the rock face altogether because the designer did not account for the slope of the rock face in relation to the lock concrete.

Both of these applications of CAD yielded important construction benefits. By segregating the rock bolts by concrete placement, Atkinson could use normal practices to manage their operations and increase confidence that the required rock bolts were in-place. Further, by detecting the improperly designed rock bolts before construction, they were able to avoid costly delays from problem identification and resolution in the field.

Other Benefits of CAD

Mr. Sale believes quite emphatically that one of the real benefits of CAD is its use as a super calculator. The use of CAD to produce lift drawings and provide dimensions for the construction forces highlighted this feature. Since they worked high off the ground, they had to generate internal control points for placing their forms and other components. The CAD "knew" the exact location of the proposed concrete faces, which were very complex shapes, and could easily and accurately calculate offsets for the field crews. Performing the same calculations manually would have been extremely difficult and error prone.

Barriers to CAD in Construction

Atkinson did not realize these benefits from CAD easily, nor does Mr. Sale believe that they will be able to use CAD effectively in many of their operations because of the major challenges that construction companies face in using CAD.

Lack of Trained People

While Atkinson employs a staff of experts in many fields, Mr. Sale believes that the successful application of CAD requires a combination of skills not normally found on construction projects. First, they need people who understand the design input, people who know what output they need for construction and people who can bring the two together. On the McKays Dam project, Mr. Sale understood the design information and could manipulate it through his programming skills to produce other information in any required format. His son understood the capabilities of CAD better and could communicate with their CAD technician. The CAD technician could make the CAD produce the output Mr. Sale and his son required given the information they provided. Mr. Sale remains convinced that these three functions are essential to employing CAD successfully and that from his experience, the combination rarely exists within a project management group.

Output

Plotting the CAD drawings also frustrated Atkinson's CAD operation. Even after Mr. Sale produced the drawing specifications for the 600+ lift drawings they required, plotting the drawings took 60 days. After they were on site constructing the dam they made all changes manually because it took too long to access the correct CAD drawing, make changes and plot the modified drawing. Consequently, none of the changes that they made on site were reflected in the CAD files for whatever later value they might have added.

Company and Job Description

Granite Construction Company (hereafter Granite) is a $650 million (volume) per year heavy civil general contractor based in Watsonville, California. They work throughout the United States on a variety of civil construction projects. Currently, they are constructing the first phase of a new transfer station between a subway system and a light rail system in downtown Los Angeles. The first phase of this project includes all excavation and concrete work for the subterranean station. They have been working on the station since early 1988 and are scheduled to finish the project in late 1990.

Key People Interviewed

Several people within Granite have played important roles in implementing CAD in their construction operations. These people work throughout the organization from division to superintendent level.

The Administrative Manager of Granite's Heavy Construction Division reports directly to the Division Manager and consequently has some influence over division policy and direction. He is not directly involved in project execution anymore but he is well aware of current operations and has long supported the use of CAD to support their field engineering work. He has been personally interested in CAD and other advanced computer technologies. Several years ago he attended a CAD seminar directed towards architects but immediately saw the potential that CAD offered to construction operations. Further, he has an artistic interest in 3D modeling and as the technology has progressed, he has begun to visualize how it could support construction. He has taken it upon himself to stay abreast of advances in CAD technology to determine if and when it advances to a point where its use in construction can be beneficial. When Granite was awarded the 7th and Flower Subway Station Project, he supported the project management's decision that the job would benefit from CAD implementation; the project's presentation and request for a CAD system was quickly approved by the division manager.

The project engineer and the assistant project manager on the 7th and Flower Subway Station Project had previously discussed the role that CAD could play in construction with the administrative manager. Together with the project manager, they decided to implement CAD on their construction project from the beginning. The project engineer has considerable project site experience and a complementary interest in computers and CAD. While he does not operate the systems, he helped with implementation and he has definite ideas about how the systems can and should be used. He has been instrumental in overcoming many of the barriers. The assistant project manager was involved here as well.

A graduate engineer assigned to the project as a draftsman/office engineer operates the CAD and performs some of the field engineering activities for the project site. He has worked on the project for almost two years, most of that time preparing lift drawings and shop drawings using CAD. He had some experience drafting in college but had never used CAD prior to this assignment with Granite. He learned how to operate the CAD entirely on his own by using AutoCAD tutorials and reading other third party books. Unfortunately, he did not have much time to learn to use CAD. After only three weeks of learning, he was forced into a production mode of drafting and has done well. He has advanced his ability slowly by additional reading on his own time and limited experimentation on the job.

Another graduate engineer is employed as an office engineer on the 7th and Flower Subway Station Project. He had two years drafting experience prior to joining Granite, and he had some CAD experience on very high end CAD/CAM applications in college. He found some of his CAD knowledge immediately useful and his knowledge of CAD and its basic abilities helped him learn AutoCAD on the job. He did not receive any formal training regarding Granite's CAD. He too had to learn on the job from tutorials and books. With some benefits from the draftsman/office engineer's earlier experience, he was able to achieve production level proficiency faster.

Evolution to CAD

Granite uses computers for a wide variety of project management and administrative functions. They have a mainframe computer for accounting and some of their estimating functions. They also use personal computers for numerous office automation tasks. Several of Granite's managers, including those discussed above followed the development of CAD over the past several years intending to implement it in their operations when the technology matured sufficiently. After being awarded the contract for the 7th and Flower Subway Station Project, they reviewed the technology and decided that AutoCAD could support their field engineering and drafting requirements.

Granite now has two AutoCAD workstations on site to support the construction at the 7th and Flower Subway Station project. They have two 386 based IBM compatible personal computers. One computer has a special accelerator and graphics controller card. One of the computers ran AutoCAD release 9, the other runs AutoCAD release 10. They ran two versions due to hardware incompatibility, but this had not created a problem. They attempted to standardize their configurations but found that release 10 was incompatible with their controller card and because of production demands were unable to fully resolve the discrepancy until several months ago. Their workstations are not networked and there is no central file system for their drawing files. They have made some use of symbols but not in a manner that allows common access by both operators. They also have an electrostatic HP draftsman plotter and a blue print machine so that they can produce any size output required on site. They feel that networking is not pertinent to the use at this site.

Applications of CAD

Lift Drawings

Initially, it was thought that CAD would be most useful for producing lift drawings. On a typical project, Granite employs a significant drafting section dedicated to producing lift drawings and they envisioned CAD improving their drafting efforts. They have used CAD for all of their lift drawings and learned many lessons. First, they confirmed that CAD does not save them any substantial time initially preparing the lift drawings but is very quick and efficient for revisions. Project engineers spend the vast majority of the time involved in preparing lift drawings researching the contract document to identify all embedments, blockouts and other requirements for a particular concrete placement. They must also coordinate to insure that any requirements by subcontractors are also reflected on the lift drawings. Actually assembling the lift drawing is only a small part of the time spent. The value that Granite now sees in using CAD to prepare its lift drawings is in gaining approval, making changes and viewing the relationships of structures at full size.

Using CAD, they draw all structures and components at their actual size. This often shows clearly where conflicts and interferences occur. They describe several instances in which the manually drafted contract documents show an arrangement that looks fine and shows dimensions. When the same information is entered into the CAD, structures drawn to the specified dimensions do not fit as nicely as originally shown. The hand drawn sketches are accurate; the CAD sketches are precise. CAD helps identify conflicts and discrepancies in the contract documents early, before the designs get to the field and such problems cause work delays. One example that they noted was the placement of a stairway in relation to another perpendicular wall. The manually drafted contract documents showed the stairs easily clearing the top of the wall while the CAD version of the design indicated an obvious conflict. Fortunately, this error never got to the field.

Traffic Control Diagram

Granite employed a cut and cover construction method for the 7th and Flower Subway Station. Since the project is located in the heart of downtown Los Angeles, city officials would not let Granite close either of the affected streets during the work day. Before the city allowed Granite to begin excavation, the city had to approve the excavation plan to satisfy themselves that traffic interferences would be minimal. The draftsman/office engineer prepared a set of traffic flow diagrams of a 12 block area of downtown Los Angeles on which he superimposed expected traffic flows during different phases of the excavation. City officials were impressed with the planning and presentation but required some slight modifications. He made the changes the same day and returned the plans to the city. The project engineer and assistant project manager believe that rapid turn around coupled with the high quality of the documents impressed city officials tremendously and laid the basis for good communication and relations.

Planning the High Angle Conveyor

An integral part of Granites' excavation plan was the use of a High Angle Conveyor. This conveyor system removes excavated material from the subterranean excavation vertically through a small opening left in the road planking. The draftsman/office engineer thinks that CAD was very useful planning the placement of the HAC. The HAC arrived on site in several pieces and had to be assembled. These pieces were modeled in the CAD and easily created layout drawings from the original hand prepared drawings by the assistant project manager for the entire HAC system. Additionally, the HAC removed spoil to a street level hopper. Both the HAC and the hopper were very heavy and required support under all points of contact. CAD allowed him to plan the location of these components. Again, this design task was simplified because all elements were drawn precisely, which avoided errors from scaling problems.

Rerouting Existing Utilities

Rerouting existing utilities that were under the roadway was a major activity that ran concurrently with excavation. Few of the utilities were located where utilities maps indicated and it was important to Granite that they be rerouted so that they would not interfere with later construction operations. They used CAD to coordinate proposed new routes for utilities with both temporary and permanent structures on the site. They feel that the preciseness of the CAD improved this analysis.

Survey Control

The survey control monumentation provided for 7th Street and Flower St. was checked and found to be different, not tied and to contain errors, which were reconciled. Some use was made in establishing construction control.

Appropriate Information to Different People

The shop drawings required by the contract did not necessarily require the same information that the crafts needed to properly construct the facility on the ground. CAD aided Granite in providing the right information to the right people. In several instances, the shop drawings that were submitted for approval had to clearly show the sequencing of operations and the interfaces with other parts of the project. These plans did not, however, benefit from the addition of the various dimensions that the crafts need to fully understand what to build. Using CAD, they were able to use the same background information and overlay other information as required. In this way, Granite provided shop drawings for review that were clear and uncluttered. With minimal additional work they developed other drawings to convey the required information to the crews.

Additional Benefits

Several benefits offered by CAD relate to most of these applications and can help reviewers consider similar types of applications. First, the fact that everything is constructed at full size helps designers and crews understand the true relationship between structures and components in the completed facility. This feature also highlights potential conflicts and interferences between between objects. Second, though dependent on the draftsman, the consistency and clarity of the information when presented on CAD drawings seemed to improve the ease of communication between all project participants from city officials down to the craft personnel.

Barriers

Lack of Experienced Operators

Granite has successfully used CAD on this project despite several obstacles that they had to overcome. First, their operators had limited or no training. They purchased the CAD and the best of available training materials and gave their designated operators a short time to reach production proficiency. Indeed, production is the high priority and the CAD operators do not have time to take training courses. The lack of time or additional resources also hindered the operators from fully exploring new capabilities such as 3D modeling.

Systems Incompatibility

Further, they suffer some slight technical difficulties because their systems are not compatible. Both operators use AutoCAD on 386 based machines but they use different versions of the software with different internal hardware additions. They are not networked so they cannot transfer files or store them centrally, but this capability was not necessary on this project, as each machine had different assignments.

Note: A video card was the only incompatibility in hardware.

Lack of Standards

They lack standard conventions and procedures so that anyone can use the system. Most items are hard-copied and therefore available without CAD on-line. The project also depends on the CAD operators exclusively for construction information. The project manager and assistants know the basics of CAD and they know that the designs they require are in the CAD, but they cannot access that information.

Note: The nature of the program's power and site use minimized the overall application of standards. The site has standardized drawing titles that enable anyone familiar with AutoCAD and DOS to access any drawing easily. The job does not shut down when an operator is off-site.

Cost

Cost is another barrier. Even with their relatively modest set up, they estimate that they have invested over $40,000 in CAD and easily quantifiable benefits are not apparent. The assistant project manager knows that that the same operators could be expected to produce the same output manually for less capital cost, but he supported the CAD use as an investment in the future, and he believes that as construction becomes more integrated into the life cycle of a facility, constructors will benefit from using CAD. They all certainly believe that CAD is qualitatively superior and there are substantial undetected savings, such as the revision process and the presentation value. The real savings will come from owner integration into the CAD process.

Areas for Future Improvements

3D Representations

The administrative manager believes that CAD will better serve construction when 3D modeling is available on site. This would allow project engineers and superintendents to view a complete model of what they are to build and walk in and around the model until they fully visualize the design intent. Such technology could also aid craftsmen in forming complex surfaces and understanding how their work fits together. In sum, 3D modeling could vastly improve communication between all project participants.

Increased Project Integration

The assistant project manager and project engineer further maintain that increased project integration will make CAD a much more valuable tool in construction. Currently, their operators spend considerable time reentering design information into a CAD system. They insist that if owners would start requiring their A/E's to use CAD and to share this design information electronically with all project participants everybody would benefit. Certainly, such a data flow would reduce the rework that Granites' CAD operators currently endure to take advantage of their CAD systems.

Improved Consistency

Note: The absence of a standard symbols library stored centrally was not a problem at this site.

Granite could also improve their CAD operations by providing more consistency and connectivity in their CAD system. They should establish drawing standards and conventions in addition to a standard symbols library stored centrally. These steps would prevent access problems when one of the primary operators is away.

Despite the remaining challenges and the room left for improvement, Granite is very progressive in its use of CAD and has positioned itself well for increased efficiency in an integrated construction environment.

Appendix C: J.A. Jones Construction Company

Company and Project Description

J.A. Jones Construction Company (hereafter, Jones), is the commercial construction subsidiary of the Jones Group, a diversified, international construction organization headquartered in Charlotte, North Carolina. One of five operating divisions within Jones, the Western Division, headquartered in Commerce, California, focuses on the Western United States. Most of their work is concentrated in the Los Angeles basin. Currently the Western Division is constructing a new private hospital at the University of Southern California medical complex in Pasadena, California.

Jones' contract involves the construction of the hospital building worth approximately $45 million. Associated contracts including over $32 million of owner supplied equipment, parking structures and site preparation raise the total cost of the hospital to over $100 million. Jones has subcontracted approximately 85% of their work to subcontractors in several major disciplines including piping, electrical and HVAC. Because of the complex nature of the hospital and the requirement to provide domestic and medical utilities, the major disciplines have been subdivided for further specialization. Jones' main challenge on the project, therefore, is to coordinate the construction efforts of many important subcontractors in the placement of many complex and tightly configured mechanical systems.

Key Person Interviewed

Rick White, Jones' Project Manager, has worked for Jones for approximately one year. Prior to joining Jones, Mr. White had extensive experience with several other California based general contractors. Mr. White studied architecture and is a licensed Civil Engineer. In addition to his construction experience, he used personal computers routinely for spreadsheet and database applications and was familiar with CAD and receptive to its use on this project.

CAD System

Jones does not own a CAD system, rather, they decided to work with CAD consultant. The CAD consultant works off site with an Intergraph workstation and produces only 2D drawings. Jones decided to use a CAD consultant because they had no experience using CAD, did not want to make a large investment in the system and training, and did not have the time to endure a long learning curve. Mr. White believes they made the right choice for their project. Their CAD consultant has supported them very well and the costs have been reasonable. Jones was able to charge their subcontractors for the CAD drawings that they received. Originally, the subcontractors balked at the added expense, but Mr. White indicated that most of the subcontractors now see the benefits of CAD and would willingly pay for the same service on future projects.

Applications of CAD

Coordinate Trades

Mr. White believes that the most important benefit that their use of CAD provided was to coordinate the many different trades working on the project. Jones' CAD consultant prepared new building floor plans based on the original contract documents but without most of the architectural notes and other information that cluttered the background. Further, in the process of reconstructing these floor plans, the CAD consultant identified many discrepancies on the contract documents. Jones was then able to request clarification from the architect to correct the discrepancies that the CAD consultant identified. The result of this process was a clean, clear set of floor plans with accurate information on which all of the subcontractors could base their shop drawings. Previously, Jones would have forwarded the subcontractors copies of the architect's sepias. The subcontractors then would have had to erase all unimportant information so that they could add their own information. Further, the old process provided no mechanism to catch errors and disseminate the correct information quickly and efficiently. Frequently, subcontractors had wrong information and different subcontractors had different information. These problems combined to generate field interferences and rework for many of the subcontractors. Their use of CAD allowed the subcontractors to plan better to avoid problems in the field.

Appropriate Information to Correct People

Another important feature of the system Jones is using is that it allows them to give each of the different subcontractors customized drawings that include all the information that they need and no information that is extraneous to their designs. For example, their plumbing and pipe-fitting subcontractors need to know the locations of walls on the floor below and above the floor for which drawing is made so that they can plan the vertical runs of their different piping systems. The HVAC subcontractor, on the other hand, only needs to know the locations of the walls below the current floor because all of their vertical runs are confined to utility shafts and all service at a given floor is provided horizontally. Further, the HVAC subcontractor needs information concerning ceiling fixtures so that he can place ductwork appropriately but the plumbing subcontractor is not concerned with reflected ceiling details. By simply and sensibly layering information within the CAD files, the CAD consultant provided customized plans for each of the subcontractors. The piping subcontractors' plans show walls above and below the floor while the HVAC subcontractors' plans show the walls and reflected ceiling plans for the floor below. All of the information that each receives is coordinated in the CAD files but each receives only what they need. Preparing such customized plans simply required the CAD consultant to replot the file with different layers turned either on or off, nothing had to be redrawn. Further, as the CAD consultant worked up from floor to floor, he could copy information that he had used for lower floors so he never had to redraw information twice but he could use it on a variety of different plans.

Improved Communication

Mr. White believes that Jones' use of CAD has greatly improved the communication between the many subcontractors. He thinks that the subcontractors began their shop drawing preparation much sooner in the construction process than they would have normally because they received clear, accurate, consistent and customized drawings. Since they started earlier with better information, Mr. White believes that they had more time to coordinate their work which further reduced conflicts in the field.

Verify Details

Jones also had their CAD consultant redraw the details for the granite cladding for the hospital's entrance. The granite pieces had to be fabricated off site so it was important that they be accurately detailed. The granite cladding was not erected at the time of the interview so the success of this application was not verified. Mr. White is confident that, because of CAD's accuracy, the cladding will go on without any problems.

Barriers to CAD

Cost

Mr. White considers cost to be one of the major barriers to increased CAD use on site. Adequate systems are still quite expensive and training people to use the system and stay proficient is also expensive. Since they have been able to meet most of their requirements using a reasonably priced CAD consultant, they cannot justify what they believe would be a much larger investment to acquire the CAD systems for themselves.

Appendix C: J.A. Jones Construction Company

Architects' CAD Practices.

Another major barrier to construction companies using CAD more is their inability to get useful design information from architects and engineers. He believes that most A/E's who use CAD at all use it for 50% to 70% of their designs, the last 30-50% is done manually because of time pressures. Therefore, he believes that even if they could get electronic data to eliminate their duplicate efforts, the drawing files would be incomplete and out of date.

Further complicating this issue, he maintains that architectural layering standards don't support the needs of construction forces. He said that where layering standards exist at all, the right information does not exist on the right layers for the constructor to easily extract the information that they need.

Company and Project Description

Kiewit Pacific is the Western U.S. arm of the Kiewit Group headquarted in Omaha, Nebraska. In keeping with the companies overall preference for decentralized operations, Kiewit Pacific is further subdivided with district offices throughout the western states. The largest of these districts in terms of volume is the Concord, California district office. The Concord office currently constructs approximately $80 million worth of facilities annually and will soon exceed $100 million per year. Each of Kiewit Pacific's district offices enjoys considerable autonomy and pursues work according to the distict level policy. The Concord District currently focuses its construction efforts in two areas: structures and horizontal construction work. The structures "areas," as they designate, constructs everything from bridges and overpasses to water treatment facilities. The grading area, as they designate their horizontal efforts, works extensively in road and highway construction and in infrastructure development for residential subdivisions.

The Concord District Office recently won a $50 million contract, as part of the joint venture Kiewit-Marmolejo, to renovate and expand the major waste water treatment facility in Oakland, California for its owner, the East Bay Municipal Utility District (EBMUD). Kiewit will do all earthwork, concrete placement and improvements to existing facilities. Major subcontractors will perform all mechanical, electrical and controls work. The structures area manager felt that this project offered them a good opportunity to experiment with the use of CAD in their construction despite the fact that the primary engineer designed the facility manually. Kiewit has one AutoCAD workstation on site to support their construction efforts and one workstation in their home office.

Key People Interviewed

Dale Stidham is the Project Manager for the water treatment project. He is a veteran Kiewit project manager who had a slight break in service with Kiewit while he worked for a Sacramento based industrial construction firm. During his "sabbatical" from Kiewit, he worked on several water and waste water treatment plants and, on his return to Kiewit, he brought with him new expertise in the construction of such facilities. Mr. Stidham has used computers for project adminstration and project scheduling but he freely admits that the idea of using CAD on a project site never occured to him. He attributes this idea to Mr. Ramsdell.

Valentin Pozin is Kiewit's Chief Structures Engineer. As a Russian immigrant 10 years ago, she and her husband accepted employment with Kiewit. She arrived a well trained engineer with little knowledge of computer applications in construction. She now designs all specialty structures required to support construction efforts and she is the Concord office CAD director. She uses CAD when she requires it and she trains other engineers in the office in its use. She has been temporarily assigned to the waste water treatement project to assist them in getting the CAD system operational.

Applications of CAD

Lift Drawings

Kiewit originally planned to prepare all lift drawings using CAD. They thought that CAD offered the opportunity to sift through the information in the contract documents and prepare the clearest most concise presentation for the field crews. While they have generally accomplished this goal, they have spent much more time than anticipated preparing lift drawings. Mr. Stidham attributes the loss of productivity primarily to inexperience managing CAD drafting operations.

Piping Layout Drawings

Another major application on this project has been in the preparation of isometric drawings for the piping systems. Kiewit categorizes the pipe on the project as either underground or above ground. All underground pipe is PVC, which they cut and fit in place. They buy bulk pipe and let the crews place the pipe with the aid of plan view drawings, which show pipe invert elevations. The plan views provided to the crews are prepared using CAD but none of the pipe sections are detailed using CAD.

Isometric drawings

Above ground pipe generally falls into two categories: flanged or welded steel. Kiewit prepares isometic drawings for all flanged pipe and forwards their isometric drawings to their fabricators for detailing and fabrication. They rely on the fabricator for all welded pipe detailing and fabrication.

Site Layout Drawings

Since the treatement plant must remain operational during construction, the owner was particularly interested in the sequencing of construction operations to assure that anticipated flows could be treated (they face substantial fines for untreated waste discharge). Kiewit's use of CAD has allowed them to provide EBMUD the plans that it needs while also using the same files to produce site layout drawings for the field crews. Generally, the layouts were the same but, using different layers, Kiewit provided different details for EBMUD than for its crews.

Further, EBMUD officials have been very impressed with the quality of the shop drawings that Kiewit has submitted. That quality, which is reflected primarily in the neatness and clarity of presentation has become the standard and now Kiewit is almost required to use CAD to maintain that quality.

Filtering Information

Mr. Stidham maintains that one of the primary functions of field engineers and their use of shop drawings is to filter information for the field crews to insure that the crews have enough accurate information to accomplish their tasks but not so much that will confuse them or overwhelm them. CAD support this goal very well. They can copy information easily to present a series of drawings detailing a specific task and they can use layers to control exactly what information is displayed for a given sequence drawing. Providing clear, accurate and consistent information is essential to keeping the field crews working productively.

Barriers

Kiewit has experienced several challenges in the use of CAD on their construction site. Most of these challenges relate to their ability to manage new and different activities and technologies on an already busy and confusing construction site.

Maintaining Trained Operators

Kiewit decided to hire trained CAD operators and have their project engineers superive them in the production of required drawings. They have found, however, that most trained operators are not trained in the construction environment and many find that environment stressful and unpleasant. Consequently, they have had trouble hiring and retaining CAD operators. Mr. Stidham also likes to run very lean project staffs which means that people need to do many different things. He likes to send a CAD operator to a supplier to pick up materials if an emergency develops, however, the CAD operators they have had do not understand that everyone on a project must work towards the project's successful completion and not be concerned with job descriptions.

Lack of Experience Managing CAD Operations

Mr. Stidham believes that one major barrier to their employing CAD more effectively is their own inexperience managing CAD. None of the project management personnel have any experience managing CAD and they have had trouble determining exactly how much they need to oversee the CAD operators to get the desired output. They have also found that because of this inexperience, they seem to have erred on the side of over supervising the CAD operation at the expense of more intense management of field operations. Mr. Stidham feels strongly that his field engineers must provide correct information to the field forces and supervise field activities. The more they are in the office supervising CAD operations, the less they are in the field. They have yet to find the appropriate balance.

Difference between Design Drafting and Field Engineering

Mr. Stidham also feels that one major obstacle is a fundamental difference between facility designs and construction drawings. He insists that the CAD operators that they have hired are very good design drafters but they prepare drawing with too many reference details, cross-sections and other distracting and difficult to interpret symbols. He believes that their construction drawings need to interpret all of these sorts of confusing design drawings and present in a few clear drawings, on a single sheet when possible, exactly what the crafts are expected to construct. Construction drawings must filter information.

Appendix E: Homer J. Olsen Construction Company

COMPANY AND PROJECT DESCRIPTION

Homer J. Olsen Construction Company (hereafter, Olsen) is a $60 million[1] (volume) Northern California Heavy Civil General Construction Contractor. They recently won a contract to construct the new $180 million Oceanside Water Pollution Control Plant (hereafter Oceanside) in San Francisco, California as the construction arm of the Olsen-Ohbayashi Joint Venture. Ohbayashi provides financial support only. The plant, designed by CH2M Hill in Emeryville, CA, will provide 43 mgd primary and secondary treatment or 65 mgd primary treatment for overflow wastewater; effluent flows to sea through an existing outfall. Olsen will perform all excavation and backfill, construct all concrete structures and place most piping systems. Subcontractors will perform HVAC, electrical and controls work and supply major components. The project employs almost two-thirds of Olsen's engineering staff.

KEY PEOPLE INTERVIEWED

Doug Kennedy is a project engineer on the Oceanside Project. Mr. Kennedy has worked for Olsen for approximately 10 years and considers himself to be in a middle group of project engineers and managers who think that computers play an important role in project management. He has been very involved with and supportive of CAD operations and has worked with the CAD manager to get the system operational. Mr. Kennedy's current responsibilities concern managing the project budget. He remains very optimistic about the potential that CAD has for the Oceanside Project and future projects although he remains skeptical that quantifiable benefits will offset the large investment in the CAD system.

Peter Alhorn, the project superintendent, another of Olsen's middle management group, is similarly involved with their CAD operations. He now works primarily in the office but his former field responsibilities and the magnitude of the job keep him well aware of how they are using CAD. During his time managing field operations he developed several innovative applications of CAD. Like Mr. Kennedy, he does not seem constrained by old ways of doing things and is able to conceive of new ways to apply the tool.

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[1] Doug Kennedy and Peter Alhorn told me that Olsen's volume was approximately $60-70 million annually. ENR's 1988 ranking of the top 400 contractors listed Olsen's volume as $56.3 million and the 1989 ranking listed Olsen's volume at $126.3 million. Obviously, this single project has skewed Olsen's volume relative to their normal volume.

Together with Mr. Kennedy, he has helped lead Olsen in implementing computer technologies as a part of project management procedures.

Gerald Clair is the project manager and an Olsen Vice President. As a senior member of the organization, he approved the use of CAD on the Oceanside project and relies on Mr. Kennedy, Mr. Alhorn and others to insure it supports the project. Mr. Clair believes that Olsen has always been a technological innovator and that the implementation of CAD was a natural step for them; this project was just the first, best opportunity. He is not involved with their CAD directly but is convinced that it has become critical to their success.

Mike McTeer is also a graduate engineer working as a CAD engineer/detailer on the Oceanside Project. Prior to working for Olsen, Mr. McTeer worked for four years as a construction detailer, first for Jacobs Associates, a San Francisco based construction engineering consultant and later as a partner in a bridge falsework design firm. He brought with him extensive CAD and computer skills and specific knowledge of customizing AutoCAD using AutoLisp. In addition to a wide variety of construction engineering applications of CAD in his previous work, Mr. McTeer has developed several innovative CAD applications on this project.

Fred Morell is a graduate engineer employed by Olsen as a CAD engineer/detailer. While he had limited experience with CAD, he was trained and worked briefly as a drafter. He is extremely interested in the work they do with CAD and wants to continue to champion its use in construction after he progresses to a field assignment.

Sy Decoy was CAD manager. He had never worked in construction before; all of his experience was in a design environment that he characterized as calmer and more organized. He had applicable experience using Intergraph Microstation and was knowledgeable in all of the systems specifics so he maintained the equipment and network and helped the CAD operators when necessary. Sy filled a new position that Olsen did not initially envision but which they quickly found to be critical to the success of their efforts to use CAD. Sy left Olsen recently citing inadequate pay and excess stress as his reasons. His position has not been refilled.

EVOLUTION TO CAD

According to those interviewed, Olsen has been progressive in its use of computers for many years. In the mid 1980's, when personal computers made job site computing viable for smaller general contractors, Olsen had a policy to charge computers and support equipment to job overhead. Consequently, project managers were slow to adopt them.

Far-sighted managers then changed their policy, and for several years agreed to provide computers to projects apart from the project budgets. This policy shift lead many project managers and project engineers to start using computers. This increased use has since permeated the company's project administration so that all project managers and engineers understand the value that computers add to their project controls systems. The company has discontinued the practice of providing computers to projects but the earlier practice of doing so created a core of project managers and engineers who support computer use and who are now willing to commit project funds to new computer resources to improve project administration.

Olsen's management had been discussing the possibilities that emerging CAD technology could have in their construction operations for several years but until this project had not acted on their earlier discussions. Several factors lead Olsen's management to believe that this project offered a good opportunity to explore the application of CAD in their work. First, the size of the job offered a profit that gave them some room to take a chance and do an experiment with CAD. So far they have committed over $150,000 to their CAD efforts but they remain convinced that the project can absorb this overhead and remain profitable. Second, they felt that CAD technology had advanced sufficiently to be a fully functional tool that they could exploit. Finally, CH2M Hill, the A/E, had used Intergraph CAD systems to design the project and offered to sell the electronic designs to Olsen for copying costs. CH2M Hill also required Olsen to sign a disclaimer relieving CH2M Hill of any liability for problems in the electronic information and confirming the paper drawings as the contract documents.

Based on these conditions, Olsen's management decided to proceed with the experiment. They initially purchased 4 Intergraph Microstation Workstations and later purchased two more and contracted with a CAD bureau for two operators with equipment, so they currently have 8 CAD workstations. Although all are Microstation capable, they run AutoCAD on three of the workstations. All of the workstations are IBM PC compatible 386-based, 33 MHz computers networked to a Sun Sparcstation 1 which has a high capacity storage device and functions as a network and file server. They hired a CAD manager to administer hardware and software and assist the CAD engineers/detailers. The network also accesses an electrostatic printer and a laser printer for hard copy output. They recently purchased a large size copier to copy original drawings.

APPLICATIONS OF CAD IN CONSTRUCTION

Olsen implemented their CAD system without really knowing what they would be able to achieve with it. They considered their use of CAD on the Oceanside project as an experiment that they undertook to determine how it could enhance their construction operations. Initially, they thought that it would greatly enhance their drafting productivity. This has not been the case but they have found numerous uses for CAD; advantages they sought eluded them while unanticipated benefits justified their optimism and investment.

Current Information to the Field

Everyone interviewed either formally or informally agreed that the primary benefit that Olsen enjoys from their CAD systems is the ability to provide clear, accurate and up-to-date information to their field forces. With the project 10% complete, they have generated 800 Requests for Information (RFI's). Of these, they have calculated that 80%, or over 600, require changes to shop drawings. They were frustrated that their initial drafting efforts realized no improvement from CAD but have found that the changes required by these RFI's are quick and easy. They average 3 days in posting RFI's to the appropriate drawings but they can make changes immediately when required.

Olsen has realized major benefits from this quick turn around of current information. Recently, one of the owner's inspectors stopped a foreman to point out a discrepancy between the work being done and the inspector's set of plans. Upon further investigation, the foreman found that he was working from the correct, most current plan while the inspector's plans did not reflect several important changes. Insuring that the field crews have accurate and current information greatly reduces the potential for rework and consequent expense.

Concrete placement drawings

Concrete placement or "pour drawings" were one of the first areas that Olsen applied CAD. Pour drawings show the basic construction sequence indicating which sections of concrete will be placed in a single placement. Concrete Pour Drawings are not new; most companies prepare them manually. Olsen's approach in using CAD, though, is new. Concrete placement drawings require considerable communication between the CAD engineer/detailer who prepares the drawing and the field superintendent who must construct the final product. Using CAD, the CAD engineer/detailer can easily adapt his plan to the requirements or desires of the field superintendent.

Further, the CAD engineer/detailer can provide more and different types of information. One of Olsen's CAD engineer/detailers has greatly expanded the use of pour drawings to assist planning and sequencing. He prepared site plans in 2D but added attribute information to designate pour numbers, section depths and pour dates. These attributes allow him to calculate the volumes of different sections easily and to designate roughly equal size placements for different days to allow them to maintain a constant crew and equipment balance.

Lift Drawings

Lift Drawings consolidate into a single drawing or series of drawings all design information such as the locations of all embedments, blockouts and other requirements of the section required to properly prepare and place a section of concrete. Generally, a project engineer who prepares lift drawings must review the contract documents to find all drawings that pertain to a given concrete section and extract and combine all pertinent information. Most project engineers prepare lift drawings manually. Since Olsen has all of the plans in an electronic format, the process is somewhat modified and has turned out to be slightly more cumbersome. After their engineers review the paper drawings, they call-up the a drawing from the file server and copy the information they need to the new drawing that they are preparing. Because of the format of the drawing files that CH2M Hill provided, they must then rescale and overlay different design data as required. Overall, the CAD engineers/detailers who prepare the lift drawings in this electronic manner do not believe that CAD is saving them any time. The time saved not redrawing a component or section is consumed in retrieving and rescaling old files. Once the drawing is complete, though, they do benefit when changes are required.

Formwork Planning

Olsen has also used their CAD system extensively to plan their concrete forming operations. While planning formwork would be done manually, CAD allows them to explore different forming alternatives. They have constructed several standard size "gang forms" that can be used in many places. In planning the formwork required for a designated concrete placement, the CAD engineer/detailer simply overlays a drawing of a form onto a drawing of the section to be placed. They can then adjust the placement of the forms to allow the crews to use pre-built forms and they can easily identify sections that require special formwork. Further, they can specify for the crews exactly where the pre-built forms should be placed relative to control points so that they can place them correctly the first time they move the forms rather than placing them approximately the first time and then adjusting them later.

Additionally, as they place the formwork overlays on the lift drawings, they can clearly see were required concrete ties may conflict with embedments or blockouts so that they can plan ahead how the ties should be reconfigured. This sort of preplanning further reduces uncertainty and confusion in the field and should improve craft productivity.

Olsen has also benefited using CAD to plan formwork placements so that the form ties create an architecturally appealing appearance. Most of their concrete is subterranean and tie spacing is inconsequential. Some of the exposed concrete is architectural. Form ties can be arrayed geometrically to create such an appearance. Olsen has used CAD to study different tie arrangements to insure that they supported the placement structurally and, where required, created a nice finished surface.

Overlays

One of Olsen's project engineers found a completely new and innovative approach to applying CAD planning a clear and grub operation for the placement of a utility trench. Prior to beginning construction, they had an aerial survey of their project site; the resulting photograph showed contour lines and was plotted at a scale of 1 in to 100 feet. The site plans that he had were plotted at a scale of 1 in to 40 feet. In manual practice, he would have had to correlate the two plots keeping them side by side. With CAD, though, he simply had the drawing replotted at a scale of 1 in to 100 feet and immediately had an appropriately scaled overlay for his aerial photograph. From this overlay, he could plan exactly which trees had to be removed to allow placement of the trench as planned. The alternatives would have been clearing a larger than necessary area, an environmentally unsuitable alternative or sending a survey crew to determine exactly which trees had to be removed, an expensive and time consuming alternative. CAD gave him access to the information he needed immediately at no extra cost.

Claims Documentation

Olsen also found CAD useful documenting a claim for extra work. Prior to Olsen beginning work, another firm had contracted with the owner to prepare the site. The contract documents that Olsen received from the owner guaranteed certain elevations on the site when Olsen began work. When they arrived on site to begin work, they found that the site had been overexcavated thus requiring them to place an engineered fill in certain areas under structures they would construct. Olsen's project superintendent quickly identified and quantified the problem using CAD. He had the contour information from the aerial survey digitized and then overlaid that information with the site plans which they had reconstructed from the contract documents. This combination of data clearly showed the extra work that Olsen was required to perform and substantiated their claim.

Stockpile Management

Olsen also combined their use of CAD with a software package for earthwork takeoff to plan their basic approach to the project's extensive excavation requirements and they are currently using it to plan backfill activities that are several years away. In planning the project and preparing their bid, Olsen engineers had two basic options, on site stockpiles or off site storage of excavated material. Off site storage required hauling and, later, backhauling and have cost $5 million. They used an earthwork takeoff package with their CAD to convince themselves that there was room on site to stockpile so they adjusted their bid accordingly. The stockpile is enormous and despite its temporary nature, required extensive shoring to allow access to construction areas.

They also plan to have a second aerial survey done in the near future. One of the things they hope to learn from this survey is the exact size of their stockpile. This information, combined with their final site plans, will tell them whether or not they have enough material to backfill the entire site as required. With this information, they plan to either identify sources for fill and contract for necessary fill at the best prices over the next few years or if they have too much, allow them to sell some of the fill. Using CAD and the aerial survey data, these calculations will be quick and easy and allow planning activities years in advance. Without CAD, such planning would never be done and the contractors would wait until the end of the project to see if they had enough fill and possibly get caught short and have to buy in a tight market.

3D Representations

Several of Olsen's CAD engineer/detailers have progressed in their use of CAD to using 3D drawings in some selected instances to show complex details or configurations. Producing 3 dimensional drawings requires considerable extra time and given the need for production, the CAD engineer/detailers have little time for 3D modeling.

In several cases though, the time investment saved valuable crew time by presenting plans in more understandable drawings. In one particular instance, the CAD engineer/detailer modeled a complex vertical section whose base differed from the top. The crafts had trouble visualizing the transition that the section had to make but when they saw the section represented 3 dimensionally, the configuration was much clearer.

Another CAD engineer/detailer modeled a portion of a complex grit digester tank support. The support had a set of irregularly shaped supports arrayed in a circle. The 3D model allowed them to explore forming alternatives and to design the formwork to simplify the placement.

3D modeling or representations have not been and probably will not be used extensively on the Oceanside project because all plans are in 2D and the conversion is very time consuming. On future projects, though, if Olsen can get full models of the structures they are constructing, they will benefit from these experiments in the use of 3D representations to improve communications to the crafts.

Survey Control

Olsen also uses their CAD to generate complete survey plans for their project. Mr. McTeer wrote a macro routine for AutoCAD that allows their chief surveyor to create survey control points easily. The surveyor simply indicates a point on a drawing and assigns it a control number, AutoCAD calculates the northing and easting of the point. After the survey designates the points he needs, he downloads the control information directly from AutoCAD to an electronic field book that attaches to his survey instrument. After he sets-up his instrument, he just accesses the control point by number and the instrument gives him an azimuth and distance. Locating the point on the ground is then a simple matter.

Traffic Plans

Olsen has also used their CAD to prepare traffic plans for the project site. The site is congested with a variety of heavy construction vehicles, supply trucks and administrative vehicles. They prepared basic traffic flow drawings using CAD. Again, these drawings would have been prepared manually and there was little advantage in preparing them initially using CAD. They will, though, realize the benefits later in the project as the site evolves and adjustments to the traffic flows are required. Such changes will be easy and quick to make.

Site Layout Plans

Similarly, Olsen must maintain site layout drawings so that they can monitor progress and coordinate work space. CAD will allow them monitor the evolution of the site and make changes quickly and easily. In its early stages, the project currently is not changing rapidly. As the contractor begins to place different structures, changes will be frequent and the benefit of using CAD in this area will become more evident.

BARRIERS TO IMPLEMENTATION

Lack of Experience Managing CAD

Following their decision to use CAD, Olsen bought the CAD systems and trained people. They had given little thought to managing the system itself, though, they quickly learned that they needed someone dedicated to running and maintaining the CAD network in which they had invested so heavily. They hired a dedicated CAD manager who helped them set up the network and establish basic procedures but he resigned after a short time. His previous experience had been in design offices and he found the construction environment, with its heavy emphasis on immediate production, much too stressful. Olsen has not refilled the CAD manager position so they now rely on several of their key CAD engineers/detailers to administer the systems. Without a dedicated manager, though, there is no one with responsibility for the entire system or capability to customize the systems and coordinate the work of the different CAD engineers/detailers.

Lack of Experienced Operators

Olsen also lacked trained CAD engineer/detailers. Intergraph trained their original set of CAD engineer/detailers on Microstation and several of the people operating AutoCAD had extensive prior experience on that system. With a single exception, Olsen could not hire experienced engineer/detailers who had CAD experience simply because of an industry wide shortage. They have consciously decided to have graduate engineers use their CAD system as their tool in detailing structures. They believe that this will produce the best results and will create a core of future field superintendents who will know how to use CAD to improve field operations.

For the near term, however, Olsen has not fully established a career progression for these engineer/detailers. They were all hired with the understanding that they would detail for a year and then rotate to a field assignment. So far, though, the demand for production has been so great that it is difficult to foresee Olsen rotating engineers and retraining a new crew in mid-project. They must determine the best way to balance the needs of the project with the career needs and aspirations of their CAD engineer/detailers.

Uncharted Waters

Since they are pioneering the use of CAD in construction operations, they had very little idea of what CAD could do for them. Several of Olsen's junior managers shared the idea and commitment that CAD should be useful in construction as well as design and they convinced senior management that they should try CAD on this project. While everyone seems excited about their CAD operations, some remain skeptical concerning CAD's ultimate value in construction. So, while Olsen has charged ahead to implement CAD to support their construction efforts, the lack of visible benefits could easily keep another firm from making the same investment. Olsen, however, is proceeding and making significant progress. Hopefully the lessons they learn will help other project engineers and other companies to view the design data in a new ways and enable them to conceive of new, beneficial ways to use that data.

Cost

Cost is a major barrier for implementing a major CAD system such as Olsen's. They jokingly refer to their use of CAD as a $100,000 experiment. Few contractors take such risks. In addition to the systems acquisition costs, they later decided that they needed a systems administrator, another unanticipated expense. Their system costs alone now approach $200,000 and will probably exceed that figure before the project is over. Mr. Kennedy says that CAD will standout as a major expense with few quantifiable benefits which obviously offset the expense.

While Mr. Kennedy cautiously believes that they will recoup the costs in construction savings, Mr. Alhorn believes absolutely that they will recover their expenses. He offered some rough figures to support his argument, the researchers expanded on his thoughts to develop the following cost comparisons. Discounting any salvage value of the system, CAD hardware and software will cost the project approximately $200,000 for the 8 workstations that they now have. Additionally, each of the CAD engineer/detailers costs them approximately $50,000 combined wages and burden annually. The average cost per workstation is $25,000, or $6250 per year for the 4 year project, or $24.00 per day (assuming 260 workdays per year) or $3.00 per hour (for an 8 hour day). The CAD engineer/detailer costs $193 per day or $24.00 per hour. Therefore, a CAD hour costs about $27.00 per hour.

The project currently employs approximately 300 carpenters. Through the project, the numbers and types of crafts will vary but will always far exceed the number of CAD engineer/detailers. Assuming that they normally have 7 workstations operational at one time, based on the 300 man crew on the project, each CAD engineer must produce plans to keep approximately 40 craftsmen busy. Carpenters cost the project approximately $40.00 per hour wages and burden, so the crew cost for 40 carpenters is $1600.00 per hour.

Therefore, the cost of the relatively cheap CAD engineer/detailer creating better, clearer, more accurate or more current data that saves the crafts time or prevents rework is quickly offset by labor savings to the project. Hypothetically, if the CAD engineer/detailer spent an entire week preparing plans that only saved the 40 man crew one hour, the project would still save money.

Despite such favorable numbers, cost is a barrier to their use of CAD because at the budgeting level, CAD appears as a constant expense with no direct savings to offset the expense. These calculations reflect an attempt to quantify unseen benefits. Olsen did not plan to for errors or rework so most of these savings will be money they did not intend to spend. As the numbers show, though, they don't need to save much time relative to their initial plan to justify the investment. (Fluor Daniel and Becthel previously told the researchers that they used to plan for 3-5% for rework on major industrial projects. On this project such a range represents $5.4 to $9 million. Olsen needs to decrease rework only a small percentage to recoup their investment.)

AREAS FOR IMPROVEMENT

CAD Manager

Olsen made a wise choice when they originally hired a CAD manager. Such a person focuses on the CAD systems to insure that hardware, software and operators support the project. Currently, CAD engineer/detailers must maintain production and they cannot administer the system to do such things as assess system capacity, establish and enforce standards and procedures, customize the system or help any of the other operators. Olsen's system of eight workstations justifies such a dedicated manager to allow other project management personnel to focus on their own work.

CAD Procedures

Olsen needs to take the time to document their system. They need to identify the procedures that work and those that are inefficient. In order to benefit in the future from this experiment, they should take with them volumes of lessons learned. As busy as they are with the construction now, they will only benefit future CAD operations if they can institutionalize the knowledge they have gained in their current experiment.

CAD Engineer

Mike McTeer has worked for Homer J. Olsen as a CAD engineer/detailer on the Oceanside Water Pollution Control Plant Project since February 1990. Prior to his current position, Mr. McTeer worked as a CAD detailer for Jacobs Associates and Loomis Associates, two different construction engineering consultants. During the four years that he worked for these firms, he applied CAD in a variety of different, innovative ways. The following examples are not presented in any chronological order and do not represent a development of CAD skills.

Applications of CAD in Construction Engineering

Equipment Planning

One of his prior clients was Homer J. Olsen, his current employer. Olsen had just won a contract for work in southern California and they needed to know whether or not the equipment that they had in the area would be sufficient. Specifically, they had a modified Caterpillar 245 excavator and they needed to know whether or not it had the reach to fully excavate a specific trench and to load haul trucks according to their proposed plan. Mr. McTeer drew several views of the trench, the excavator and the trucks to simulate all operations in just 2 dimensions in any view. CAD allowed him to copy and rotate the excavator arms to show its actual reach from any position. This analysis convinced Olsen's project manager that their excavator would be able to perform the necessary work and that they would not need to haul one of their larger excavators to southern California or to rent one in the area. This applications demonstrates the versatility of CAD and that its real limits lie in the imagination and skills of the operator. Mr. McTeer's analysis cost system and operator time but saved them haul expenses and gave the project management confidence that they could accomplish the project without excavating difficulties.

Construction Sequence Planning

In another CAD application, Mr. McTeer produced a set of working drawings which showed the sequence of work for a complex tunnel paving operation. CAD made the production of detailed working drawings a rather simple matter of moving components within a drawing, adding specifics where necessary and adding explanatory notes. CAD saved this effort considerable time because of the ease with which components can be copied or moved.

Bridge Falsework Design

Mr. McTeer worked extensively detailing bridge falsework for Loomis Associates. He developed several libraries of symbols that specifically support the use of CAD to design bridge falsework. He also found CAD useful in several new ways. On one project, he designed the falsework for a complex parabolic bridge support. Using CAD, he was able to detail the falsework simply and accurately. The bridge support, though, was quite high and they wanted another margin of safety for their work so they employed CAD in still another way. They plotted their basic designs of the bridge support, the element which their falsework had to support, at full size, 1 in equals 1 in. This gave them stack of plots with just a few lines, each senseless on its own. They then laid the entire bridge support plans out on a large parking lot and precut and assembled their falsework. This allowed them to work at ground level and insure that all pieces fit. This same operations would have been much more difficult in place fifty or one hundred feet high.

Mr. McTeer has also used CAD to assist in the design of bridge falsework. In one instance, he used CAD to calculate all column loads so that his partner who was actually designing the timber members of the structure knew exactly what loads he had to design the selected configuration. Further, CALTRANS required calculations of column loads for the falsework before construction began so that they could be confident that the falsework was properly designed. Mr. McTeer simply designated tributary areas of the structure loading each of the columns, added parameters for materials and depths of structures and the CAD calculated the column loads.

In a similar application taking advantage of the calculating power of CAD, Mr. McTeer used CAD to adjust the falsework to account for bridge camber and to assist in designing camber shims. In designing the falsework for a bridge with a vertically curved road surface, he had to account for the use of straight bridge girders, bending deflection of the girders and settlement of the falsework under load. He used CAD to plot curves representing the proposed road surface, the deflected beam elevations and the settled falsework which then allowed him to calculate easily the size camber shim required at any location to insure that they designed road elevation was achieved. The same calculations could have been performed manually but they would have been very difficult and time consuming.

On another falsework design, he created a scaffolding symbol to assist him in planning the required bracing for the symbol. When the symbols were configured to certain spacing, a mark appeared on the symbol indicating that the braced length had been reached which then signaled him to add appropriate bracing. He indicated that such a cross check was very important since many bridge failures result from improper bracing and subsequent support buckling.

On a final falsework design project, Mr. McTeer took advantage of CAD's ability to track components to both create materials lists for the falsework and more importantly, to work backwards from existing materials lists to design the falsework. He wrote a CAD macro routine that tracked the materials used and listed the available materials. Using this routine, he was able to design falsework that used materials that the contractor had on hand. Mr. McTeer felt that this capability was important because it prevented contractors from spending extra money on new materials and perhaps more importantly, it required crews to build the falsework as designed rather than improvising to employ available materials, a process that could lead to falsework failure.

Company and Project Description

Charles Pankow Builders, Ltd (hereafter Pankow) is a $650 million dollar per year design-build contractor. Although they commonly refer to themselves as a design build contractor, they actually do not design facilities, rather, they hire engineers to design the structures they will build. They remain responsible for both design and construction.

Pankow primarily constructs concrete structures throughout the western United States and does a considerable amount of its work using precast concrete. Generally they precast their own concrete components on their project site when conditions allow. They also buy precast pieces from other suppliers when such arrangements best fill their needs. Pankow has been particularly successful in applying its knowledge of precast concrete engineering to the construction of parking garages.

The researchers visited a construction project for one such parking structure in Brea, California. Pankow contracted for a major modification of the Brea Mall, most of which was to be concrete construction. To date, they have constructed two concrete parking structures and the project under review is the third of four that they will construct. The project is an 800 car precast parking structure. All columns, girders and decorative exterior panels were precast and erected. The parking slabs were placed conventionally on the erected skeleton.

Project management consisted of a Project Superintendent to whom a project engineer and a field superintendent reported. Two field engineers, one designated as responsible for all precast operations and a second responsible for in-place concrete construction reported to the project engineer. The field engineer responsible for precasting operations saw the repetitive designs of the columns and the exterior panels as an area that could benefit from the use of CAD.

CAD Champion

Brian Feigenbaum was the primary force behind the automation of field engineering using CAD on the Brea Mall Parking Structure Project. Mr. Feigenbaum is a trained architect who decided to move into construction. During his years as a young architect for Skidmore Ownings and Merrill, he learned and used various CAD systems. He later obtained a Masters Degree in Construction Management and wrote a master's degree thesis on the application of Apple Macintosh Computers in Construction. He joined Pankow following his graduate schooling and became a field engineer.

Mr. Feigenbaum brings several interesting skills to the project office. As an architect, he understands design methodology and how to make drawings convey the intent of the design. He complements this knowledge with his intense interest in computer applications in construction. An enthusiastic proponent of computers in construction with intimate knowledge of CAD, Mr. Feigenbaum quickly recognized the potential for CAD in his field engineering work.

As the Precasting Engineer, Mr. Feigenbaum was responsible for preparing lift drawings for all precast columns and exterior panels (because of site constraints, they bought the large precast beams from a local precast company). Both the column and panel designs were very repetitive so he immediately knew that CAD could simplify his precast drawings.

Computers and CAD

Pankow has used computers for many other project management and administrative functions. Their application of CAD on the Brea Mall Project, however, was a direct result of Mr. Feigenbaum's desire to use CAD. The company made no commitment to CAD nor was there even any corporate decision to explore its potential in their work. Prior to starting work with Pankow, Mr. Feigenbaum worked temporarily as a computer consultant. As a consultant, he acquired a powerful array of Macintosh hardware and peripherals including external storage devices, a two page monitor and a laser printer. Mr. Feigenbaum brought his own hardware to the project site for use on company business. He was able, however, to get the project superintendent to agree to buy the CAD software that he wanted; they bought VersaCAD for the Macintosh. So, with Mr. Feigenbaum's impressive hardware set-up and the companies minimal investment in software, they were set to use CAD on site.

Mr. Feigenbaum has been an Apple enthusiast for many years. His recent work with CAD and his knowledge of the current state of computer technologies, though, make him question whether or not the Macintosh is the best platform for their CAD operations. He suggested that the company would have to do more analysis before it commits to one system or another. At least he has gotten the process started.

Applications of CAD

Column Grid Layout

One of the first applications of CAD on the Brea Mall Project was to establish the grid layout of the columns. The parking structure has an irregular footprint with several 45 degree changes in direction. The exterior panels were still required to meet flush at all corners. Using CAD, Mr. Feigenbaum was able to calculate the column offsets required to allow the exterior panels to meet as required. Basically, he started from the exterior of the building and worked inwards. After establishing the exterior of the building, he was then able to place the columns and orient them correctly. Finally, it was a small task to measure the offsets of the corner columns from the orthogonal grid that governed most other columns. While this application seems simple, the same work done manually would be difficult and time consuming, for Mr. Feigenbaum it was quick and easy. This application highlights the use of CAD as an excellent calculator. A designer need only place objects at full size where he wants them and then measure to determine exactly where they are, a simple but powerful capability.

Precast Concrete Components

Most of the rest of the application of CAD on the Brea Mall project involved the precasting operation. Mr. Feigenbaum had to insure the 120 columns and 112 exterior panels were all accurately detailed, placed and installed. Of the 120 columns, there were approximately 12 different types. There were 17 variations of panels.

The columns were far more complex to detail than the panels. Some of the columns had over one hundred embedments in addition to the reinforcing steel. Embedments included such things as connectors for threaded rebar to allow continuous reinforcement into shear walls, shear plates, tubular blockouts at appropriate angles for post tensioning cables and lifting device anchors. Different configurations of these embedments existed in the 12 different types of columns. The columns varied in their overall height and in the location of corbels (seats for precast beams) in as many as three different directions at two different levels.

CAD aided Mr. Feigenbaum significantly in two different ways. First, since he detailed everything full size, he could see immediately where interferences would occur and resolve those before they got to the precasting beds and caused project delays. Second, while overall dimension of the columns varied, one dimension, the distance between corbels, did not vary. Consequently, the differences were above the top corbel and below the bottom corbel. VersaCAD has an associative dimensioning capability that greatly aided the modifications required for the different columns. By just changing one of the measured distances, VersaCAD automatically adjusted the drawing. Mr. Feigenbaum, therefore only had to "click" on the dimension to be changed, type the new dimension, and his column was resized. This seems like a simple capability but what would have been a time consuming task of modifying all the different drawings became a relatively simple operation. To assist him in his detailing efforts, Mr. Feigenbaum also established a library of the symbols that he needed for the columns and panels. Therefore, he was able to resize a column as required and place the appropriate embedment symbol on the drawing and proceed.

In addition to the features of CAD discussed her, Mr. Feigenbaum used Microsoft Excel to determine exactly what the dimensions of the columns should be. He got an elevation plan for the site and the layout grid for the columns from the engineer. He input this information into a spreadsheet for which he had written an extensive macro program and the spreadsheet calculated the exact dimensions for each column. Using Multifinder on the Macintosh, he displayed this spreadsheet next to his CAD drawings and simply changed the dimensions of the columns as indicated on the spreadsheet, saved the drawing and continued to the next column.

Mr. Feigenbaum also experimented with a new Parametric Design program that he purchased. This program lets him define a component in terms of variable dimensions. He then inputs the dimensions into a tabular input form and the Parametric Design Package, running on top of VersaCAD, draws the component to the correct size. He lacks only an interface between the table of column dimensions that he created in the spreadsheet and this parametric design package to have a fully integrate/automated column design procedure.

Concrete Placement Planning

Mr. Feigenbaum also used CAD to calculate the areas for concrete placements. The Project Engineer wanted to plan the sequence of concrete placements. He also wanted to insure that the placements were as equal in size as possible given some structural constraints so that they could maintain a steady work force. While most project engineers would just carve up the concrete plan views into roughly equal areas, Mr. Feigenbaum was able to use his CAD in its role as a super calculator to test several different placement configurations. Calculating areas and volumes for a specified plan area is a simple matter. He tested 5 or 6 different sequences before they settled on their final plan.

Appropriate Formats

Finally, Mr. Feigenbaum used CAD to produce drawings that were convenient for on site use. Mr. Feigenbaum's first duty was to provide construction information to his precasting superintendent. Thereafter, he had to inspect for quality and accuracy. As references for his detailed designs, he produced a set of notebooks that showed all column or panel pieces and all embedments from three different plan views. He provided the dimensions that he knew were critical to the correct placement of the embedments and the corbels and any other dimensions that the precasting superintendent wanted. All of these drawings were produced on 11x17 paper and placed in notebooks, a convenient format for carrying around the project site. This configuration was driven in part by his constraint to a normal Apple Laserwriter and their office copy machine but this constraint did not hamper their operation at all. Actually, this format keep the plans neat, clean and useable throughout the project.

Quality Control

Mr. Feigenbaum also insisted that his use of CAD improved their quality control. Because he spent less time drawing many different components, he was able to put more time in making his CAD drawings more accurate and complete. His drawings then became a quality control document. He used them as a checklist to insure that all required embedments were properly placed prior to placement of concrete.

Summary of Benefits

Mr. Feigenbaum took advantage of many of the capabilities of CAD. First, using CAD, he was able to detail all components at full size. This eliminated potential scaling errors and immediately showed any conflicts between components in the same plan view. Second, he took maximum advantage of the repetitiveness of his designs. He established a library of standard symbols which then only required that he select them from a menu rather than redrawing them each time. He also used the associative dimensioning capability to ease the process of making changes in the various column dimensions. Finally, he turned his plotting constraint into an asset by producing plans in an easily accessible, easy to use format.

Barriers

Lack of Company Commitment

Despite his overall success using CAD, Mr. Feigenbaum does admit some difficulties that he had in using CAD in their construction operations. High among the difficulties was Pankow did not have a corporate desire to use or explore CAD so he was forced to provide the bulk of the system assets (all of the hardware) to get the system working. Now, the company sees great benefit in using CAD but only because of Mr. Feigenbaum's extraordinary initiative and commitment. Further, while the company did provide the software, they did not provide any training or additional time for Mr. Feigenbaum to learn how to use the CAD system. Consequently, he spent many very long weeks maintaining detailed design production while he learned how to use the CAD. Despite his prior experience with CAD, it took several weeks to achieve reasonable level of proficiency.

Lack of Other Champions

Another barrier was the lack of other champions within the company. While Mr. Feigenbaum found CAD to be particularly useful and effective, no one else on the project team learned to use the system and none of them will be able to expand the system to other jobs sites. Their success with CAD was due to Mr. Feigenbaum alone and did not benefit from the synergy of several people seeking a common goal.

Technical difficulties

Several technical issues also eluded solution. He never figured out how to plot details of different sizes on a single plot. Since everything is kept in the CAD at full size, he could not plot a full component and a blown up version of a detail on the same plot. He resorted to manual cutting, pasting and copying. He also did not have time to attach attributes to the symbols and components for database extraction. He manually counted symbols to develop the list that he included on each plan. None of these problems significantly affected progress but they frustrated the champion and illustrate that they did not fully exploit the CAD because they relied on only one man's efforts.

Future Improvements

CAD has a bright future in Pankow. Mr. Feigenbaum recently presented his work at a company annual meeting in Hawaii. Many of the other project engineers expressed an interest in learning more. Additionally, Dean Stephan, the company Vice President, notified the researchers of Mr. Feigenbaum's work, an indication that he sees its value and potential to their work.

For CAD to be more beneficial on any project or throughout Pankow, the company must make a commitment to it. They cannot rely on individuals to provide thousands of dollars worth of hardware and countless hours of extra time to make a system succeed.

Appendix H: Summit Constructors, Inc.

Company Description

Summit Constructors, Inc. (hereafter Summit) is a $50 million (volume) per year, employee-owned, Denver-based general contractor. They primarily construct municipal water and waste water treatment facilities throughout the western United States. Summit's management sees municipal waste water treatment facilities as a slow growth sector in the future and environmental forces are causing more private companies to treat their own wastes before dumping them into municipal systems. Because of evolving market and political conditions, the company management has begun to focus marketing efforts in the private water and waste water treatment projects. Summit boasts a very lean and flat organization with only two to three levels of management between the CEO and the project manager.

Their minimal home office staff includes a three person design department that supports all projects with detailed design and working drawings. Several forces drive their detailed design efforts. First, most of their work has been on public projects and specifications generally allow the contractor to select "or equal" equipment. The contractor must then adjust the piping system to meet the particular geometric requirements of the equipment they choose. Second, their projects increasingly include modifications or renovations of existing facilities. They must modify the design to account for in-place conditions found through on-site investigations. This force then couples with a third more general trend that Summit has identified: A/E's are providing less complete designs. Summit personnel believe this is an attempt by A/E's to cut their engineering costs. Summit must compensate for less complete designs by increasing their detailed design efforts, or, in the case of retrofits, making more extensive site investigations. Together, these forces generate a requirement for extensive detailed design by Summit's design section. In addition to detailed designs, the design section must also prepare standard shop or working drawings for their field forces. These requirements for design services place a tremendous demand for production on the three person design section.

Analysis

Summit's lean organizational structure and employee ownership allow them to be flexible and relatively uninhibited by organizational bureaucracy in the introduction of new technologies and procedures. Their lean structure, however, also limits their in-house technical expertise and since all members of the organization must constantly produce, changes and advances are made only through the initiative of personnel willing to invest additional time and effort. Any asset that can improve their design production can significantly improve overall company operations.

Key Personnel Interviewed

David Klodt, Summit's design manager has worked for the firm since the mid-1970's and has witnessed the company's evolution through different markets and owners. Throughout his career at Summit, he has filled a variety of positions and has gained critical knowledge of all of the companies operations, which enhances his abilities as the company's head designer. He began as a drafter and, with no formal training or guidance, has become an extremely proficient system designer. Mr. Klodt was always interested in computers and stayed abreast of current CAD technologies out of personal interest. He jumped at an opportunity offered by one of Summit's vice presidents (no longer with Summit) to buy a CAD system.

The company bought AutoCAD software but did not provide any formal training or time to learn the system. Through his own initiative, Mr. Klodt did AutoCAD tutorials and experimented on his own time to build his CAD proficiency. He took AutoCAD classes but found them to be very basic and unproductive for him. Finally, after he felt comfortable with the system, he started using CAD for all of his drafting needs.

Mr. Klodt manages the CAD section very independently. He receives minimal instruction from above and primarily works with project mangers and engineers to fulfill their needs. He was never directed to implement CAD, rather, after gaining confidence with the system, he decided when the time was right for full scale implementation. He has also trained two additional CAD operators who function in a drafting mode only; he still must make or review all design decisions.

Walter Balcer is Summit's Vice President for Project Development. Although he has only been with Summit a relatively short time, his role in marketing the company, coupled with the company's shift to more private work caused him to seize Summit's CAD capabilities as a marketable distinction for their company. He has been very active in promoting Summit's CAD capabilities by producing brochures highlighting their use of CAD and marketing this competency to potential clients. He highlights the value that their system creates for the client by improving construction and procurement operations and offering the potential for increased integration with other project participants. Mr. Balcer is very optimistic about the potential benefits and uses of CAD in their operation.

Richard Clark is Summit's Vice President for Operations. Mr. Clark is responsible for home office operations and supervising some of the project managers. While generally less enthusiastic about the role that CAD plays in Summit's operations than Mr. Balcer, he does support its use for definite benefits that they currently realize and the potential it offers for improvements in other areas of their operations. Mr. Clark is an important player in Summit's use of CAD because he is solidly grounded in daily operations and all functions that affect construction progress. He tries to keep their use of CAD focused and supportive. He is also extremely interested in technologies to improve materials management, an area that could benefit substantially from the integration of CAD-based detailed design and other project management functions.

Alan Fisher is a Summit Vice President and Project Manager. Mr. Fisher is the company's "Devil's Advocate" for technological matters. He does not think that computers are the panacea for project management difficulties and he tries to keep the use of CAD in proper perspective. He supports CAD but highlights that it is primarily an automation of tasks that they formerly performed manually. He also insists that Mr. Klodt's ability as a designer, not CAD, is the secret of their design success.

Analysis

Together, these four people guide and execute Summit's design and construction operations. Generally they recognize the benefit of using CAD in their design section but there seems to be a healthy tension between them concerning the value of CAD and technology in supporting their work. This tension keeps the company focused and allows the design section to progress in its application of CAD. Together, Mr. Clark and Mr. Fisher balance Mr. Balcer's enthusiasm for CAD and try to keep the company's efforts directed towards profitable construction. They also force corporate introspection to insure that Mr. Klodt's use of CAD supports their construction efforts.

Computers and CAD

All of the interviewees insist that Summit has always had a progressive attitude towards the use of computers in their work. All those interviewed maintain that the company has used computers for project management for many years. They currently use Lotus Symphony, an integrated software package, for most of their project administration needs. They also use "PAYDIRT," a digitizer-driven software package for earthwork takeoff and estimating and Lotus Symphony in their estimating operations. They enjoy a very high availability of computers; almost everyone with a need or a desire to use a computer has one.

Approximately three and a half years ago, one of the companies vice presidents approached Mr. Klodt, the design section manager, to ask if he was interested in learning

CAD. Mr. Klodt's positive response led to their acquisition of AutoCAD to run on existing hardware. Since then, CAD has become the exclusive design and drafting tool.

Summit's design section now consists of three people: a design manager and two CAD operators. They operate three 386 based IBM PC compatible personal computers running AutoCAD release 10 in a stand alone mode. They have no network, server or libraries of files or symbols. The design manager began as a drafter and became an excellent designer through years of training and exposure to design issues. The CAD operators had minimal CAD experience and no design experience prior to working at Summit. Mr. Klodt has taught the CAD operators his system and basic design knowledge while maintaining production through their busy schedule. The design section no longer has any manual drafting boards or capability.

Analysis

Summit summit currently uses CAD effectively and their projects now rely on an automated design section. Mr. Klodt is an extremely critical member of Summit's organization. Not only does he manage their CAD operations but he is their head designer. He appears to be irreplaceable from within the organization and it would be difficult for Summit to find an outsider who could fill his position either as a designer or head CAD advocate. Advancing CAD falls exclusively to Mr. Klodt. He implemented and manages the system and his initiative controls the pace, and in most cases, the direction of advancement.

Applications and Benefits

Designing for "Or Equal" Equipment

As previously mentioned, most specifications for the public facilities that Summit constructs allow the contractor to select equipment to meet general performance criteria. Equivalent equipment, though, frequently has different geometric dimensions and requirements than equipment suggested by the A/E. Summit must reconfigure any parts of the associated piping systems to accommodate the requirements of the selected equipment. Prior to their use of CAD, they would have done this manually. CAD has brought several advantages over manual procedures. First, CAD requires drawing a component only once. Thereafter, they can copy the component quickly, easily and accurately. Further, although they do not design in three dimensions, CAD allows them to copy dimensions between different perspectives to maintain the integrity of the design in different dimensions. Mr. Klodt and his CAD operators do not believe that they save much time in the initial drafting effort using CAD because most they spend most of the time searching for relevant design information in the contract documents. They do maintain though that they benefit when they can reuse parts of a design or when they must make changes to earlier drawings.

Accommodating As Built Condition

As previously mentioned, Summit constructs many renovations and retrofits to existing facilities. As A/E's try to reduce costs, Summit has found that the A/E's do less field investigation for these projects and in many cases merely indicate the end points of a pipe and its specifications. Consequently, Summit personnel must make more extensive site investigations. They actually benefit from these investigations. Since all CAD designs are done at full scale, they only need to enter key dimensions of the existing facility. Then they can design their pipe systems with confidence that they will fit accurately. This gives them a very accurate design of the system, which is much easier and faster for their field forces to construct.

Layout drawings

Summit has also found that its site layout drawings are much more accurate and therefore more useful because of their use of CAD. First, since they can reuse backgrounds, a little extra effort creating a background pays dividends on different site drawings. They can put less information on a given drawing to keep the presentation clear and avoid cluttered and confusing drawings. Producing extra drawings is a simple matter of turning different CAD layers on or off and replotting the file. Second, since designs are done to full scale they can clearly visualize the relationships between all structures and facilities on the site. They have found that the accuracy of the relationships of objects drawn in their proper places at full scale is a major benefit of the use of CAD and improves construction operations considerably.

Survey Grids

From site layout drawings, Summit can easily generate site survey plans for their field crews. These plans are developed in either polar or rectangular coordinates. Recently, they have constructed several sludge digesters and found that they can easily produce a layout grid for the digester based on the center of the tank. These grids then allow the field crews to establish accurate string lines and place forms or components quickly and more accurately.

Detailed Design for Fabrication

Summit benefits tremendously using of CAD to detailing their pipe spools. Most of the pipe that they use on waste water treatment plants is cement lined, ductile iron pipe.

This type of pipe is normally shop fabricated and assembled on site. Most constructors would send the fabricator the contract documents and the fabricator would detail the spools. Summit details their own spools and just requests fabrication. Summit's use of CAD is vital in this application because of the accuracy that they system provides. CAD allows them to accurately dimension spools to account for all fittings, flanges, valves and gaskets. Further, since Summit details their own spools, the spools are fabricated to support the construction scheme that Summit establishes, not a scheme envisioned by a fabricator.

Summit's detailing procedures also include a numbering scheme for all pipe spools and system components so that when they arrive on site, the site superintendent can easily identify a piece and determine exactly it belongs. This system has the additional benefit of allowing Summit to adjust its crew balances to include fewer expensive pipefitters and more, less costly laborers. This is possible because they have, by their designs, reduced the construction operations to an assembly process rather than the more traditional cut and fit process.

Coordination of Trades

Summit has also benefited from their use of CAD in coordinating the work of subcontractors. Although Summit does not transfer plans electronically to any of its subcontractors, they are much more confident in the dimensional accuracy of their shop drawings, which they provide to their subcontractors. The subcontractors then know exactly where Summit will install its systems and equipment and where the subcontractors should place theirs. This system is enhanced by Summit's use of easily reproducible backgrounds to provide less cluttered and better coordinated drawings of different piping systems.

Lift Drawings

Summit also uses CAD to prepare concrete lift drawings that detail a section of concrete to be place and show all embedments, blockouts and other forming considerations. Although they do not include embedments required from subcontractors, they do provide their subcontractors copies of all placement plans and details of the work that Summit personnel will perform. This helps coordinate the work of different subcontractors on a single concrete placement. Summit believes that their use of CAD in this area greatly improves communication between them and their subcontractors. Since many of their projects are in restricted areas or in existing facilities with limited laydown areas, this communication and coordination insures that the subcontractors only bring to the site the components they need for current activities.

Schedules

Summit also used CAD to draw logic networks for their CPM schedules. Summit has used several different scheduling packages and recently settled on Primavera. Earlier packages, though, did not have good presentation capabilities and the networks that they produced through printers, though logically correct, were very hard to read and follow. Summit's management wanted the networks to be easy to follow so that field personnel would use them so they had the design section redraft the networks on the CAD to present the schedule information more clearly.

Analysis

Without any comprehensive plan for using CAD, Summit has discovered many important uses for CAD in supporting their construction operations. It is reasonable to assume that, given a more thoughtful approach to CAD, they would think of and implement even more applications that support their work. Further, with a little extra effort, they could integrate their spool detailing with other materials management databases. Summit has incorporated their CAD capabilities into their marketing approach, including it as an element of their company strategy could also yield important benefits.

Benefits from CAD

Summit's success using CAD highlights three primary benefits that CAD technology offers to construction forces. First, CAD drawings are dimensionally accurate. Since CAD drawings are made to full size, there are no scaling errors either in inputting the design or taking dimensions from the drawing. Further, improved dimensional accuracy supports their prefabrication efforts and makes error and interference detection easier, even in just two dimensions.

Second, CAD has improved communications between project participants both internally and externally. Their use of CAD allows them to provide, at little cost in time, more drawings with less cluttered and confusing information, which improves the readability of the plans and therefore overall communication of the design. They believe that the clarity of their shop drawings speeds the turn around time when they must submit shop drawings to the owner for approval. Similarly, providing such plans to subcontractors allows Summit to communicate and coordinate different activities more efficiently.

Finally, Summit benefits from CAD's ability to copy and reuse different drawings easily. While there is little savings in time using CAD for drafting a component, they save considerable time and effort when they can reuse components that they have already drafted. They reinvest much of the time they save providing more information to the field crews, which improves overall construction operations.

Analysis

Summit rediscovered many of the often claimed benefits of CAD. Their lack of an implementation plan indicates a lack of a formal prior awareness of these benefits. Perhaps if they study CAD technology more, they will discover other capabilities of CAD that could enhance their operations.

Barriers

Despite their overall success using CAD, they have experienced several difficulties implementing their CAD system. While they have overcome most of these barriers, some still plague their operations.

Lack of an Implementation Plan

Summit encountered numerous barriers to implementing and advancing their CAD-based design operations. First among these barriers was their lack of an implementation plan. They never really implemented CAD, rather, they just bought it and waited for Mr. Klodt to begin to use it. They never reviewed their total system requirements to balance hardware and software, they have just acquired systems haphazardly. They never planned for any formal training and they never set any goals for what they wanted CAD to do for them (although they can see many of the benefits now). They don't have a formal plan for where CAD will go within their firm. Mr. Klodt has some ideas about where it can go but the company needs to insure that his ideas complement the overall company strategy.

Lack of Experience CAD Designers

Another major barrier has been finding people to operate their CAD systems. Mr. Klodt and others in management cite a critical shortage of trained designers to hire into their operation. Consequently, they have hired people with limited CAD training and must teach them both how to operate in Summit's system and how to make sensible design decisions.

Lack of Control Over Design Section

A third obstacle to their use of CAD has been a lack of control on who accesses the CAD section. Mr. Klodt seems to work for nobody and everybody. He gets requests for many different types of support such as drawing logic networks, organizational charts and other business graphics that do not require CAD but which greatly distract the design effort away from design support. This is an easy trap to fall into when a new tool has such powerful capabilities. Managers must insure that the tool is used for the tasks which provide the greatest return. Summit's management has recognized this problem and begun to deal with it.

Project Manager Misconceptions

Summit also needs to train its Project Managers and Project Engineers regarding what they are doing with CAD in the design section. The PM's and PE's need to understand the system capabilities and weaknesses so that they can request design information that best supports their construction efforts. One project engineer spent an entire evening manually scaling and checking all dimensions on a drawing that had been produced using CAD. He did not find any errors and if he had understood the system and its dimensioning capabilities, he could have save a lot of time. Further, if they knew the capabilities of CAD, they could ask for additional information that could support their construction work better.

Lack of a Symbols Library

Summit has not invested in a standard library of symbols. Instead, they recreate much of their design new for each project. Since they do many similar treatment plants, they could benefit from a symbols library.

Analysis

Summit rediscovered many of the difficulties that other companies have had using CAD. If they had developed an implementation plan, they could have thought through many of these difficulties and not had to "reinvent the wheel." As a pioneer in the use CAD in construction, Summit could not draw on the experiences of others in directing their CAD efforts. They should thoroughly review their progress and plan more for the future of the CAD efforts.

Areas for Future Improvement

As outsiders looking in, the researchers can see several areas in which Summit could improve the efficiency of its design section's use of CAD. Obviously, Summit's management should consider these and decide where to allocate resources to best support their overall company strategic plan.

Hardware Configuration

One important area that offers potential for improvement is in the configuration of their systems. They could benefit from a networked environment based on a file server that contains all project drawing files. This would simplify file management and give the drafters and designers better and quicker access to the information that they need.

Symbols Libraries

This configuration would also support the use of a symbols library which they should invest more time in developing. They could take greater advantage of CAD's duplication capabilities in using a symbols library. Such libraries are commercially available or could be developed in house if additional assets were provided.

Database Attributes

Another area in which they could improve is in utilizing the CAD database. They stated a desire to improve materials management. They could easily add attribute information to components in their designs and this information would then be available, from AutoCAD's database to other database applications. By investing in available databases to integrate their drawing files with procurement and materials management databases, they could improve overall operations significantly.

3D Designs

They could also benefit from the use of 3D designs. Since they do not design complete facilities, AutoCAD should be able to adequately handle pipe system designs in 3D. This would enhance their detailed design process and further improve the constructibility of their designs.

Strategy

Finally, they need a CAD strategy. This strategy must be specific to the company but it should consider the following: how can and does CAD support construction operations, how should the CAD section be staffed, how will training be provided, what new capabilities are needed and how will they be developed/acquired and implemented.

Integrating the Construction Process

During the A/E/C SYSTEMS '90 trade show in Atlanta, Georgia, the Integrated Construction Association sponsored a concurrent conference discussing "Integrating the Construction Process." This conference featured a series of speakers with experience in the construction industry who share a common view of an integrated construction environment. Two of the speakers discussed work that relates directly to this research on the applications of CAD in construction. Most of the other speakers focused on the more general benefits of an integrated construction environment and the difficulties achieveing that integration.

Applying the 3D Model at the Construction Site

Bill O'Brien, a student research assistant for Professor F.H. "Bud" Griffis at Columbia University in New York City, described research that they are currently conducting concerning the potential applications for using 3D modeling to support construction. Working closely with Columbia's facility engineering staff and Stone & Webster Engineering Corporation, they selected a new building under construction on Columbia's campus as the subject of their investigation. Professor Griffis and his research assistants have taken the contract documents for the structure and are creating a 3D model of the building using the CATIA, a powerful mainframe based CAD system. They began with the hypotheses that their 3D model would allow for better constructibility reviews and more effective construction planning and simulation.

They use the 3D model to maintain both geometric and nongeometric data on the structure and its components. The model supports construction directly with the production of perspective veiws, renderings, orthographic, isometric, elevation and detail drawings. Further, they have included in the model's datebase information such as component numbers, model names for equipment, equipment locations, specification numbers, purchase order numbers, work package designations, delivery date requirements and operations and maintenance data.

They propose that the information within the model should assist project managers plan work, schedule and sequence tasks, coordinate different trades, estimate materials and costs, assess changes, report progress and monitor interferences. So far in their work, they have used CAD to effectively assist the project managers in planning tasks and assessing the impacts of changes.

In downtown New York City, the construction forces work in very tight areas. They used the model to plan the flow of concrete trucks around the construction site during foundation placement. Using their model, they determined the best access for the trucks and the number that could be waiting at any time.

After construction had begun, Columbia decided to add an additional boiler to the mechanical room to allow them to sell steam to an adjacent building. The original boilers had already been placed and much of the surrounding structures were underconstruction. They used to model to see how the additional boiler could be placed without removing any in place strutures. They discovered that if they proceeded with construction, they would place a concrete beam that would interfere with their movement of the boiler into position. Upon further analysis, however, they determined that if the beam were redesigned to offer greater clearance, they could proceed with construction and still be able to place the boiler. This sort of analysis demonstrates one of the more powerful applications of full 3D modeling in construction.

The project has also benefited from the translation of 2D contract documents into a 3D model. Research assistants spend much of their time coordinating data from different contract drawings to accurately model the data. Frequently, they discover interferences, inconsistencies or errors on the contract documents. Discovering these types of discrepencies before they cause construction delays improves field productivity and offers a major incentive to this sort of analysis.

Taking the Electronic Model from Design Concept to User Occupancy

Mr. John F. McKenna retired from C-E Lummus after many years managing design and construction. He also lead their efforts in the early 1980's to implement CAD into their design operations. Currently, he runs a CAD consulting firm, CAP/CADECS.

Mr. McKenna said that CE used 3D modeling for complete detailed design down to the point of designing connections and specifiing bolts. He said that they use their 3D detailed designs to significantly alter the conventional construction contracting sequence. First, they now produce all steel fabrication drawings and they have fabricators bid on actual fabrication. They improve the process by removing the redundancy of design efforts and having the structure detailed and fabricated the way that they want to construct it.

They have taken this approach even further and contracted with their constructor for labor only. CE provided all materials based on their detailed designs. On one mechanical contract they prepared materials lists for everything, including connecting bolts. They then contracted only for labor. They experienced total changes and additions to the $15 million of only $15,000. CE's system eliminates duplication in taking-off materials and detailing components . On another project, the only difference in labor bids was the cost of bolts, which the designers forgot to include on thebill of materails. The designers recalculated the materials take-offs including bolts and the labor contracts were much closer.

CE's approach further enhances their construction because the accuracy of their detailed design allows them to fabricate more of their work off site and reduce the construction efforts more to assembly. Difficult tasks are removed to shops where accuracy and quality can be controled more closely. Further, CE's system allows their construction managers to get they information they need in any format. They can get take-offs for any particular area of the project or they can focus on particular systems.

Finally, Mr. McKenna believes that using 3D modeling for detailed design allows them to include construction input into their designs so that they design a facility they way they want to build it, rather than figuring out how to build a facility after it has been designed.

Appendix J: Sample Interview Questions

1. What was your Project Engineer's job description?

2. What types of facilities do they design?

3. Are they familiar with microcomputers and computers in general?

4. Is knowledge of microcomputers or CAD required for hiring a project engineer?

5. Do you integrate any microcomputer functions? If so, which ones and how?

6. How do you (or do you think) that CAD could be used on project sites?

7. What is your project organization? Who is responsible for designing? Who is responsible for computers? Do you communicate with your home office using computers?

8. To what extent do you use subcontractors? How does this affect your use of CAD?

9. What types of organizational barriers do you see in bringing CAD to the project site? Would Superinetndents resist it?

10. How could computers and CAD be used to improve communications between project personnel?

11. How do you get the data files? Do you have to pay for them? How are the contract documents changed if at all?

12. How technical do you think the people have to be to use CAD?

Report on Survey of US and Japanese Construction Companies

Introduction

In order to get a better perspective of how construction companies use CAD, the researchers surveyed construction companies in the U.S and Japan. The survey participants were not selected statistically or scientifically. The researchers arbitrarily selected construction companies with annual revenues over $100 million on the assumption that these companies could afford CAD if they saw any value in it. The researchers intended to learn from the survey how companies use CAD, how they think it could be used, what problems they have faced in implementing CAD or what problems have prevented their use of CAD.

Methodology

The researchers conducted the survey in two phases. The data collection phase involved developing, distributing and receiving the survey questionnaires. The analysis phase involved synthesizing the data to find trends and specific applications of CAD.

Collection

The researchers developed a questionnaire based on a review of current literature concerning CAD use in construction and and initial interviews with construction firms using CAD (a copy of this questionnaire follows this introduction). The questionnaire first asks about computer and CAD use and then it focuses on barriers to implementing CAD. Essentially the same questionnaire was distributed to both US and Japanese companies. A few improvements were made to the questionnaire for Japanese companies based on early input received from US participants. All questionnaires to each company were mailed concurrently but the responses returned over several months. After the rate of return of fell significantly, the analysis phase began.

Analysis

The analysis phase involved several activities. First, the researchers consolidated the response data in a spreadsheet. Then, the data was exported to a simple database for initial analysis. The results of the initial data analysis were then graphed using a graphing program. Finally, the researchers reviewed the results to assess pertinent findings. This process was iterative because several analyses suggested new ways to review the data so the researchers returned to the data to make new analyses. The graphs of answers to the survey questions and the conclusions that the researchers draw from those findings follow this narrative. The responses were analyzed by size, type of company as appropriate. In several cases, the researchers analyzed the responses to questions based on whether or not the respondent indicated that they used CAD.

Participant Profile

Survey Questionnaires were mailed to 380 U.S. construction firms and 365 Japanese construction firms. The U.S. firms were selected from the ENR Directory of Contractors: all those with annual revenues over $100 million were included. The Japanese companies were selected from a similar reference ranking Japanese contractors annually.

Significant Findings

The analysis yielded many findings concerning how US and Japanese companies use computers and CAD in construction and the difference in attitudes and applications between the two countries. Although the survey was not designed to compare US and Japanese construction companies, some interesting findings in this area arise.

- US construction companies use computers for more different applications than Japanese companies but Japanese construction companies use CAD more than US construction companies.

- More civil contractors use CAD than building or industrial contractors in USA.

- Small US companies report having higher percentages of people who are very competent using computers. Perhaps this is because smaller companies use computers more to leverage the skills of the people the have.

- One fourth of medium and small US construction companies have no interest in using CAD.

- Civil contractors report the lowest portion of projects designed using CAD but they still use CAD the most in their work.

- Few participants think that preparing shop drawings manually is efficient, regardless of whether or not they use CAD or prepare shop drawings.

- Most Japanese construction companies have used CAD to prepare shop drawings.

- Large companies see more potential for CAD in construction than small or medium companies.

- More Japanese companies think than CAD benefits construction than US companies.

- Perceptions of barriers vary greatly by size of company.

- Large companies don't think that price is a major problem.

- Larger companies believe that resistance to change is more of a problem than small companies.

- In the US, the companies that use CAD are not bothered by potential barriers as much as the companies that use CAD. (The perception of problems has changed as they use CAD.)

Conclusions

Based on these general findings, the researchers have formulated several conclusions:

- The high response rate indicates great interest in this area.

- Many construction companies see great potential for CAD to improve their field operations but they are struggling to implement it.

- Some differences exist between US and Japanese construction industries but both are struggling to implement CAD into their construction operations.

- Computers are an integral part of construction management tools

- Companies throughout the industry have experienced the same problems that the researchers found in the interviews.

Survey Improvements

While this survey found some very interesting results, the researchers found that the survey process could have been improved in several ways. In retrospect, the questionnaire should have been developed more. The method of analysis should have been established prior to finalizing the questionnaire and the questionnaire should have been modified to support the intended analysis. Questions should have been reviewed more carefully insuring that all possible answers were included and that all answers pertained directly to the question asked. Better proofreading would have eliminated typographical errors and ambiguous questions. The survey population should have been selected more scientifically. A random cross section of the industry may have provided more consistent and valuable information. Finally, more complete participant profile data should have been solicited.

Survey Format

Appendix K: Survey Results

Please Answer Questions on Both Sides

SURVEY QUESTIONS

RESPONDANT'S NAME:
RESPONDANT'S JOB CATEGORY:
a. manager/executive b. CAD supervisor c. project manager
d. CAD operator e. project engineer f. others( )
COMPANY NAME:
TYPES OF CONSTRUCTION: Building, Industrial, Residential, Civil
RESPONDANT'S TEL NO.:

Section I: CURRENT USE OF COMPUTERS AND CAD IN CONSTRUCTION

Please circle all appropriate answers for each question.

1. How much do you use computers to directly support construction?

a. alot b. some c. not much
d. not at all

2. For what sorts of applications do you use your computers systems to support construction?

a. word processing d. estimating
b. spreadsheets e. scheduling
c. database f. CAD
g. others( )

3. How would you assess the computer literacy of the people on your construction project teams?

a. very competent
b. minimal computer skills
c. no computer skills

4. Do you have any people in your construction organization who know how to use CAD?

a. yes, and we use it in construction
b. yes, but we don't use it in construction
c. no, but we plan to train people to use CAD
c. no, no one has expressed interest

5. How many of the projects you contructed were designed by A/E's using CAD?

a. some b. not many c. none
d. don't know

6. (To those who circle either a or b in question 5) What kind of projects is CAD used for?

construction category: a. building
b. civil c. industrial,
d. other____________________.

6. con't.

project size: a.large b.medium
c.small d.regardless of size

type of CAD: a.2D-CAD b.2.5D-CAD
c.3D-CAD d.others( )

7. Have you ever tried to get electronic design information from designers or engineers?

a. yes, we have gotten electronic design information for internal use
b. yes, wehave tried but designers did not cooperate
c. interested but have not tried
d. not interested

8. Do you use CAD to design any temporary structures on your projects such as formwork, scaffolding, shoring, retaining walls, coffer dams or other temporary structures?

a. yes. For what structures:
____
____
b. no, but it may be a good idea. For what structures?
____
____
c. no, have not considered it.
d. no, because it does not sound productive

9. Do you use CAD for shop drawings or detailed engineering?

a. no, we don't prepare shop drawings or do detailed engineering
b. no, we do these things manually and don't need to change
c. no, we prepare them manually but may switch to CAD
d. yes, we use CAD. if so, which type? (__________________)

Please Answer Questions on Both Sides

Please Answer Questions on Both Sides

10. How do you prepare as-built drawings? Would CAD help in preparing them?

   a. manually
   b. A/E takes care of them
   c. don't usually prepare as-builts
   d. CAD would be helpful in preparing as-builts

11. How do you communicate change orders with the A/E?

   a. mostly by telephone
   b. mostly in person
   c. usually don't need to communicate with A/E
   d. mostly with FAXed information
   e. via computers with modems

12. Do you think that CAD could help you plan your construction operations better?

   a. much b. some c. none d. don't know

13. (For those who circled 12 a. or b.) For what kind of operations would CAD improve planning?

   a. coordinate work spaces
   b. prepare concrete lift drawing
   c. track as-built changes
   d. monitor and control site layout
   e. analyze crane and forklift use
   f. planning concrete pumping operations
   g. robot control
   h. survey control
   i. others
   (____________________)

Section II: PROBLEMS/BARRIERS TO USING CAD TO SUPPORT CONSTRUCTION

What do you think problems introducing CAD to the project sites are or would be?

Please choose one level and fill the blank for each item, referring the following explanatory notes.

a. absolutely yes **b.** yes **c.** neutral **d.**no **e.** absolutely no **f.** don't know

(___) 1. Little productivity improvement in CAD

(___) 2. Lack of the internal company and external industry standards about the use of CAD makes implementation difficult

(___) 3. High cost for the introduction of CAD (costs outweigh benefits)

(___) 4. Lack of people who know how to use CAD

(___) 5. Too complicated and difficult to learn CAD

(___) 6. Lack of cognizance of use working system by the introduction

(___) 7. Fear of change of working system by the introduction of CAD

(___) 8. No contract requirement for Architect/Engineer to provide contractor electronic data inhibits CAD use

(___) 9. Legal and technical problems in transferring design data to site such as designing ownership and data integrity, etc inhibit implementation of CAD

(___) 10. Hard to convince project managers that upfront costs are defrayed by downstream benefits

11. Others
(___) ____________________
(___) ____________________
(___) ____________________
(___) ____________________
(___) ____________________

If you have any other comments on the use of CAD to support construction operations, please write them on another sheet of paper and return with this survey.

Who else in you organization besides the respondent could we contact for more information on how your company uses CAD in construction.

Name:
Phone:

Please return this survey in the enclosed addressed and stamped envelope to John J. Mahoney, Construction Engineering and Management Program, Department of Civil Engineering, Stanford University, Stanford CA, 943050-4020 (415)-723-1957/4447

Please Answer Questions on Both Sides

＜両面の質問にご回答下さい＞

回答者名：＿＿＿＿＿＿＿＿＿＿＿＿　電話番号：（　　）＿＿＿＿＿＿

会社名：＿＿＿＿＿＿＿＿＿＿＿＿

業種：（該当するものすべてに○をつけて下さい）
　ａ．ビル建築　ｂ．プラント・工場　ｃ．住宅建築　ｄ．土木
　ｅ．設備関係　ｆ．その他（　　　　）

回答者の業務内容：（該当するものに○をつけて下さい）
　ａ．社長・重役　ｂ．ＣＡＤ管理者　ｃ．現場所長・工事責任者
　ｄ．ＣＡＤオペレーター　ｅ．公務主任　ｆ．その他（　　　　）

Section I:　施工におけるコンピュータおよびＣＡＤの利用状況に関する調査

それぞれの質問に対し、貴社の該当する答えのすべてに○をつけて下さい。

１．施工を支援するために、どの程度コンピュータをお使いですか。
　ａ．多い　ｂ．多少　ｃ．少ない　ｄ．全くない

２．施工を支援するために、どのようにコンピュータを利用していますか。
　ａ．ワープロ　ｂ．スプレッドシート（コスト、数量などの管理表）
　ｃ．データベース　ｄ．積算
　ｅ．工程管理　ｆ．ＣＡＤ　ｇ．その他（　　　　）

３．貴社の施工現場における人々のコンピュータに関する能力をどう評価しますか。
　ａ．十分な能力　ｂ．必要最低限度の能力　ｃ．全く能力なし

４．貴社の現場関係者でＣＡＤを使用できる人がいますか。
　ａ．いる。実際に、施工においてＣＡＤを使っている。
　ｂ．いる。しかし、施工においてＣＡＤを使っていない。
　ｃ．いない。しかし、ＣＡＤを使用できる人を教育する予定である。
　ｄ．いない。誰もＣＡＤに興味を示していない。

５．施工したプロジェクトのどの程度が設計段階でＣＡＤにより設計されていましたか。
　ａ．大部分　ｂ．多少　ｃ．少し　ｄ．なし　ｅ．不明

６．（質問５でａ，ｂ，ｃのいずれかに○をつけた方のみお答え下さい）
　どのような種類のプロジェクトにおいてＣＡＤが用いられましたか。
　タイプ：　ａ．ビル　ｂ．土木　ｃ．プラント・工場　ｄ．住宅　ｅ．その他（　　）
　規模　：　ａ．大規模　ｂ．中規模　ｃ．小規模　ｄ．規模に関係なし
　ＣＡＤの種類：　ａ．２次元　ｂ．２．５次元　ｃ．３次元　ｄ．その他（　　）

７．貴社は設計者から設計情報を図面や計算書ではなく、磁気テープやフロッピーディスクやモデムなど電気的な方法で受け取ることを試みたことがありますか。
　ａ．試みた。実際に電気的な方法で設計情報を受け取ったことがある。
　ｂ．試みた。しかし設計者が協力的でなく、できなかった。
　ｃ．関心はあるが、試みたことはない。
　ｄ．関心ない。

８．貴社の現場において、型枠、足場、山留め、締切りなどの仮設構造物の設計をＣＡＤで行っていますか。
　ａ．行っている。　対象構造物は：＿＿＿＿＿＿
　ｂ．行っていない。しかし良い考えである。　対象構造物は：＿＿＿＿＿＿
　ｃ．行っていない。仮設構造物の設計にＣＡＤの利用を考慮したことがない。
　ｄ．行っていない。仮設構造物の設計にＣＡＤを使用しても利益につながらないと思う。

９．施工図や詳細図の作成にＣＡＤを用いていますか。
　ａ．用いていない。なぜなら、施工図や詳細図を描くことがないため。
　ｂ．用いていない。手作業で作成しており、ＣＡＤに変える必要を感じない。
　ｃ．用いていない。手作業で作成しているが、ＣＡＤに変える予定である。
　ｄ．用いている。　ＣＡＤの種類は：＿＿＿＿＿＿

＜裏面の質問にもご回答下さい＞

<両面の質問にご回答下さい>

１０．竣工図をどのように作成していますか。ＣＡＤは竣工図の作成に有効でしょうか。
ａ．現場で手作業で作成している。
ｂ．設計者が作成している。
ｃ．通常は竣工図を作成しない。
ｄ．ＣＡＤは竣工図の作成に有効と思われる。

１１．設計変更についてどのような方法で設計者と連絡を取っていますか。
ａ．ほとんど電話を使用　　ｂ．ほとんど設計者と会うことにより
ｃ．通常は設計者と連絡を取らない　　ｄ．ほとんどファクシミリを使用
ｅ．モデムを用いパソコン通信も利用　　ｆ．その他（　　　　　　）

１２．現場における諸作業を計画する際にＣＡＤは有効であるとお考えでしょうか。
ａ．大変有効である　ｂ．ある程度有効である　ｃ．有効でない　ｄ．わからない

１３．（質問１２でａまたはｂに○をつけた方のみお答え下さい）
どのような現場作業の計画においてＣＡＤは有効であるとお考えでしょうか。
ａ．作業のスペース上の競合の調整
ｂ．コンクリート配筋詳細図作成（パイプ等の貫通やパイプ吊下げ用アンカーを考慮）
ｃ．原設計の変更　　ｄ．現場内レイアウト計画
ｅ．クレーン使用計画　　ｆ．コンクリートのパイプ圧送計画
ｇ．ロボット管理　　ｈ．測量計画　　ｉ．その他（　　　　　　）

Section II: 施工へのＣＡＤ利用に対する問題・障害に関する調査

下記の項目のそれぞれが、施工現場へのＣＡＤ導入に対してどの程度問題・障害となっているとお考えですか。次の凡例を参照して、（　　）にａ～ｆのうち１つ記号をご記入下さい。
また、その他に問題・障害と思われることがありましたらご記入下さい。

<凡例>　ａ．まさにその通り　ｂ．その通り　ｃ．どちらともいえない
ｄ．あまり関係ない　ｅ．全然関係ない　ｆ．わからない

（　　）１．ＣＡＤにより生産性がほとんど向上しない。
（　　）２．ＣＡＤの使用に関する業界全体および社内標準が欠如。
（　　）３．ＣＡＤ導入のための費用が高い（導入費用が利益より大きい）。
（　　）４．ＣＡＤ使用方法のわかる人間が不足。
（　　）５．ＣＡＤの使用方法が複雑なためその習得が困難。
（　　）６．ＣＡＤに関する重役の認識不足。
（　　）７．ＣＡＤ導入により引き起こる組織改革に対する不安。
（　　）８．設計者から施工業者に電気的な方法（フロッピーディスク、パソコン通信）で設計データが引き渡されることを要求する契約が不足。
（　　）９．設計データの所有権や管理方法など、設計データを現場に引き渡す際に生じる法的および技術的問題。
（　　）１０．ＣＡＤ導入の初期コストが後の利益により還元されることを現場所長に理解させることが困難。
（　　）１１．現場へのＣＡＤ導入のための強力な牽引者が欠如。
１２．その他
（　　）＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿
（　　）＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿
（　　）＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿

Section III:　施工におけるＣＡＤの使用に関してコメントがございましたらご記入下さい。

<同封の封筒にてご返送下さい。ご協力ありがとうございました。>

General Findings from Survey Questions

Findings from Tables 1-3 and Figures 1-4

Participant Profile

Survey Questionnaires were mailed to 380 U.S. construction firms and 365 Japanese construction firms.

The response rates were

U.S. 158/380 = 41.7%
Japan 137/365 = 37.5%

- The profile of the individuals who answered the questionnaires differs considerable between the U.S. and Japan. Almost two-thirds of the U.S. questionnaires were answered by people who classified themselves as managers/executives while CAD managers answered the largest share of the surveys returned from Japan.

- The relative proportions of respondents by size is fairly constant between the U.S. and Japan

- Therefore, we can compare the responses from the U.S. and Japan regardless of the size of the companies

- The questionnaire did not ask company volumes. Volumes for US contractors were taken from the 1990 ENR Top 400 contractors: 116 of the 158 respondents were listed, 42 remain unknown and are not represented in these proportions. Volumes for Japanese contractors were obtained from an industry newspaper that published annual revenues.

- The survey sent to Japanese companies included an additional category for the type of company to include specialty contractors.

- All of the U.S. contractors, and all except four Japanese contractors, who indicated that they do residential construction also indicated that they do building, so these two categories were combined for all further analyses. The categories were combined into the building category

- Totals in Figure 3 equal more than 100% because many companies indicated that they do several types of work.

- Fourteen of the U.S. respondents did not indicate what type of work they do so they have not been included in this calculation.

- Distribution of respondents by type and size are almost the same between the U.S. and Japan so we can compare the results directly.

Table 1 Distribution of Companies by Type and Size (USA)

	Small	Medium	Large	Unknown	Total Number
Building	42	39	13	18	112
Industrial	32	29	13	14	88
Civil	15	18	8	14	55
Others					12
Unknown					14

<Notes>
Size Small: annual revenue = $100M - $200M
Medium: annual revenue = $200M - $1,000M
Large: annual revenue = $1,000M -
Categories of type of company are not independent

Table 2 Distribution of Companies by Type and Size (JAPAN)

	Small	Medium	Large	Unknown	Total Number
Building	34	31	23	0	88
Industrial	23	21	12	0	56
Civil	35	30	16	0	81
Specialty	19	36	14	0	69
Others					19
Unknown					0

<Notes>
Size Small: annual revenue = $100M - $200M
Medium: annual revenue = $200M - $1,000M
Large: annual revenue = $1,000M -
Categories of type of company are not independent

Table 3 Distribution of Companies by Size

Annual Revenue	USA	JAPAN	Size of Category
$100M - $200M	52	53	Small
$200M - $300M	17	16	Medium
$300M - $400M	16	14	
$400M - $500M	4	7	
$500M - $1,000M	10	21	
$1,000M - $2,000M	7	8	Large
$2,000M - $3,000M	3	10	
$3,000M - $5,000M	3	2	
$5,000M - $10,000M	3	5	
$10,000M - $15,000M	1	1	
Unknown,	42	0	
Total Number	158	137	

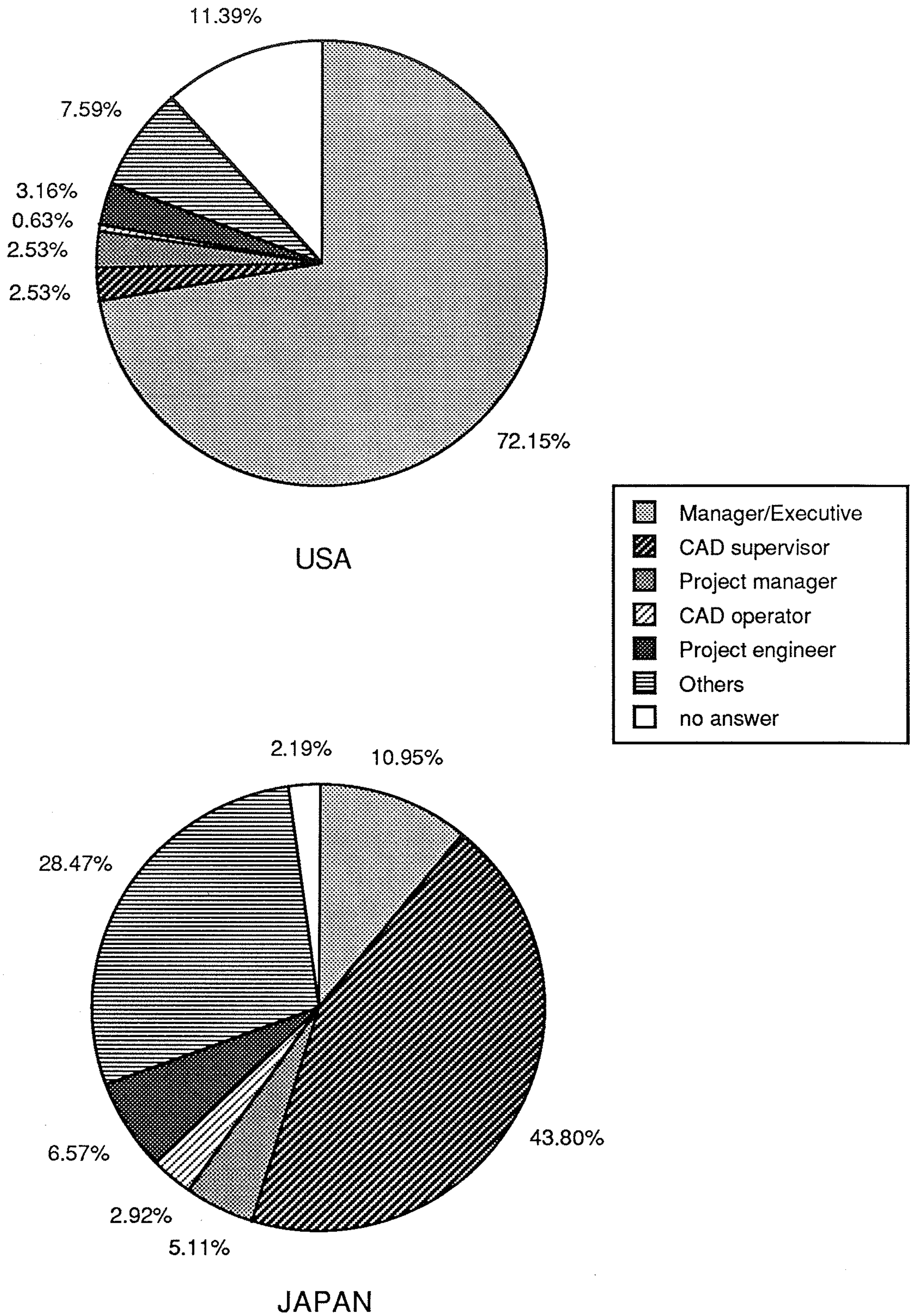
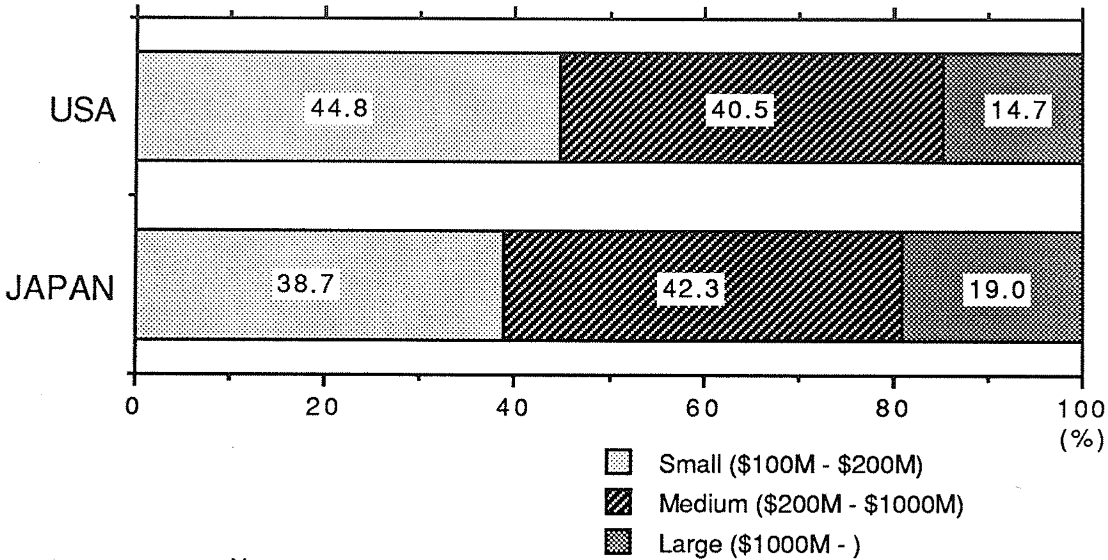
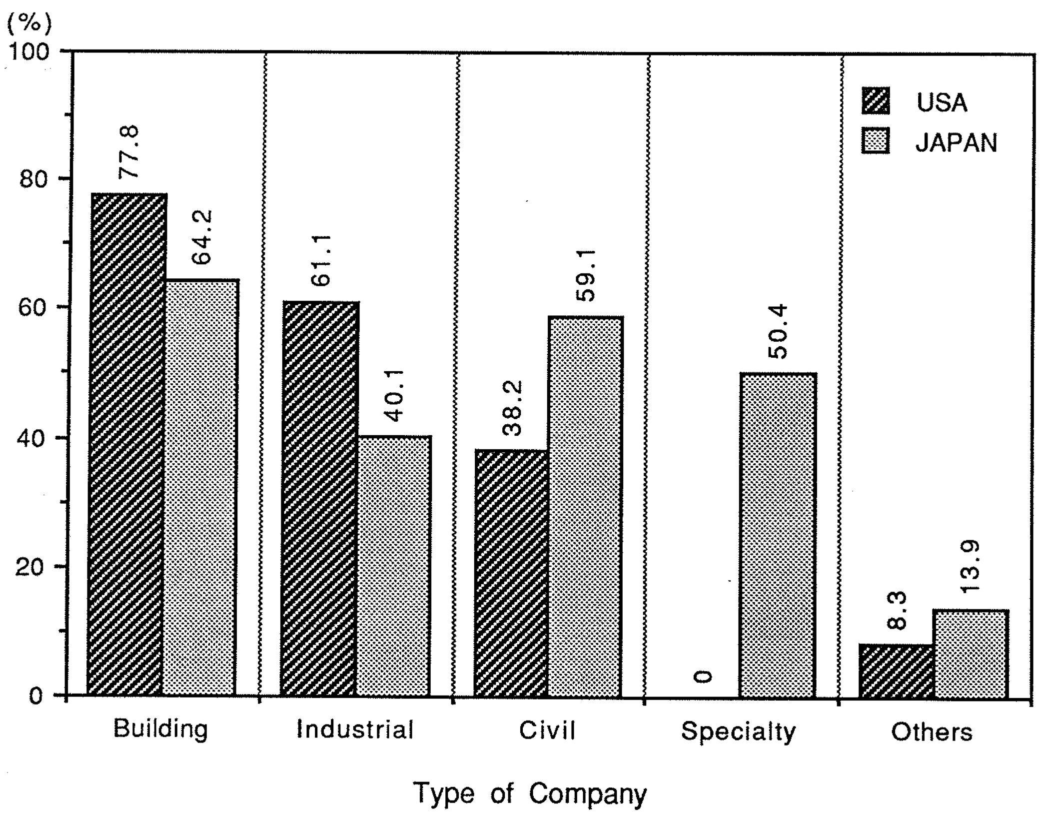


Figure 1 Distribution of Respondents by Position of Individual Answering Survey



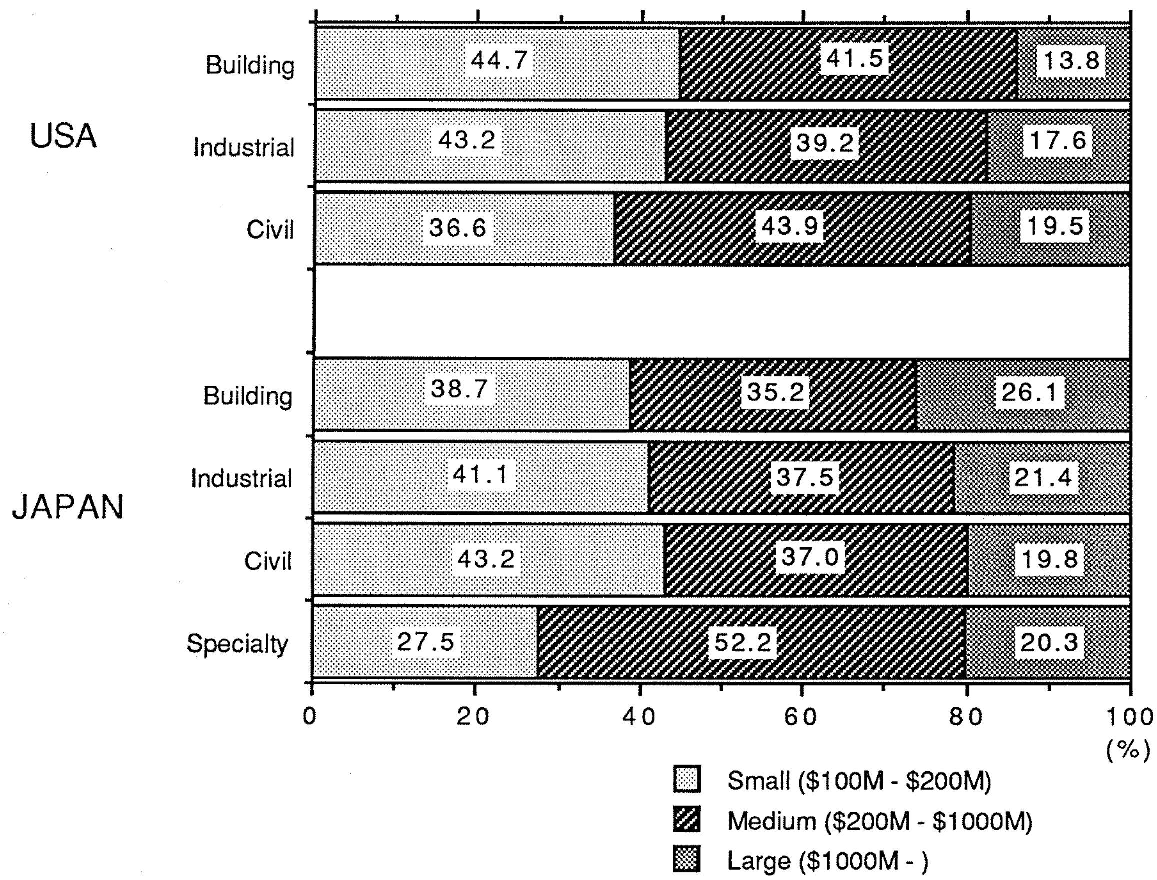
<Notes>
- Classification of size of company based on annual revenue

Figure 2 Distribution of Respondent Companies by Size



<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

Figure 3 Distribution of Respondent Companies by Type



<Notes>

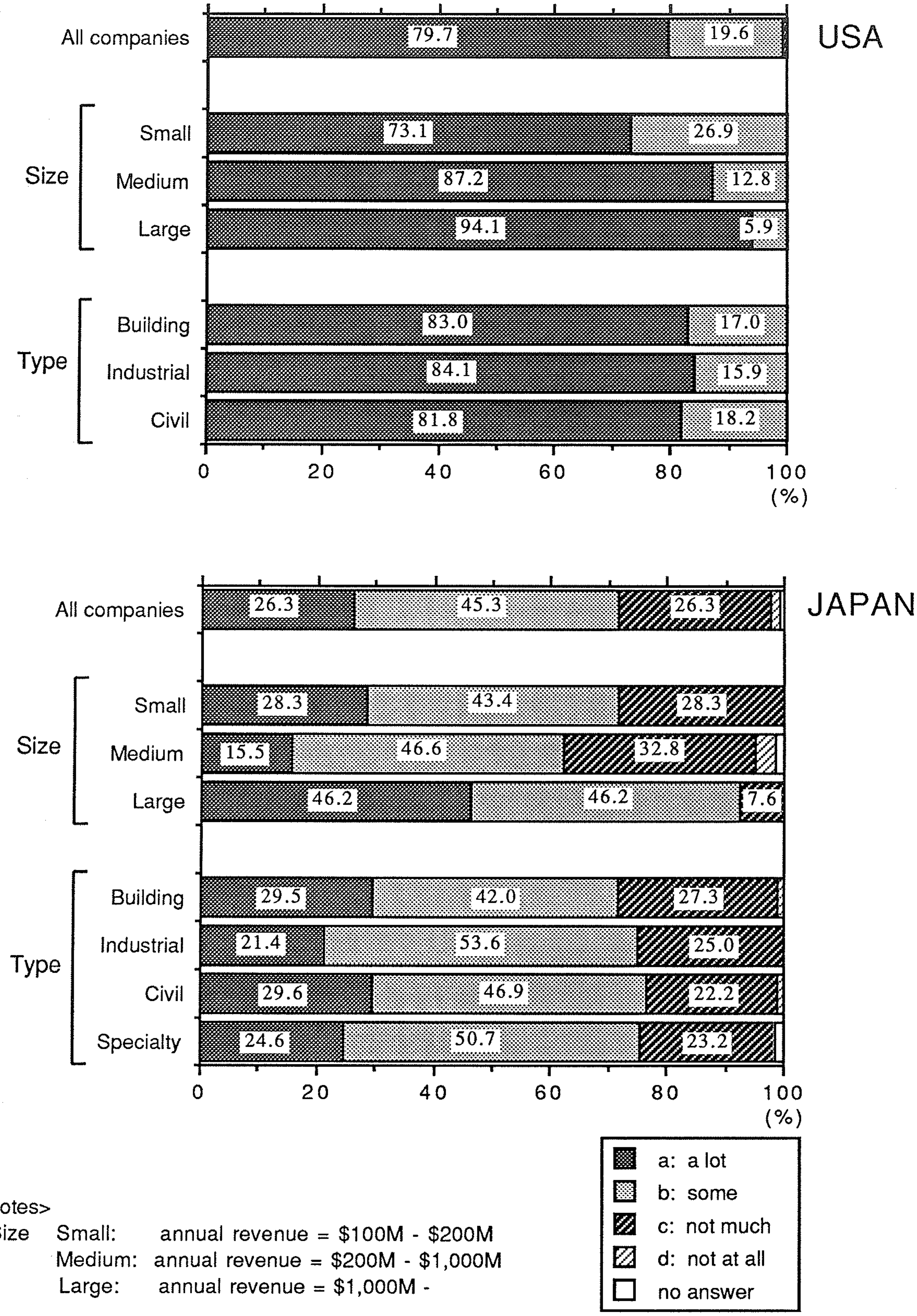
- Classification of size of company based on annual revenue
- Specialty on Japanese survey only

Figure 4 Distribution Respondent Companies by Type and Size

Findings from Figure 5

Question 1: Degree of Computer Use on Construction Sites

- All respondents use computers "some."
- The vast majority say they use computers "alot."
- No real difference between different types of companies
- Almost all companies use computers.
- Most only use computers "some."
- Only large companies report the largest percentage using computers "alot."
- No real difference between types of companies.



<Notes>

- Size Small: annual revenue = $100M - $200M
  Medium: annual revenue = $200M - $1,000M
  Large: annual revenue = $1,000M -

- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 5 Degree of Computer Use on Construction Sites (Question 1)

Findings from Figure 6-8

Question 2: Current Computer Applications in Construction

Note: Totals equal more than 100% because companies use computers for a variety of applications.

- U.S. firms use computers more for basic functions than the Japanese companies do. Possible reasons for this may be that computer keyboards do not support Japanese in using computers for most functions. Most Japanese people resist computers because of the unfamiliar and awkward keyboards.

- Japanese companies report using CAD more than U.S. companies: 75%-v-43%

- Japanese do not use computers much for scheduling because there are few good scheduling packages in Japan.

- Little difference in computer usage based on size of company except in use of CAD for US companies.

- Large US companies use CAD more than smaller ones.

- Large companies use computers most in each category followed by smaller companies and then medium companies. Perhaps this is because the larger companies have the money and smaller companies have greater incentive to leverage the work of their limited number of employees.

- All sized Japanese companies use CAD relatively the same amount.

- For Japanese contractors, the largest difference in CAD use is between civil and specialty, only 16%.

- More US civil contractors use CAD than US building or industrial contractors. Perhaps this is because civil contractors subcontract less of their work and maintain the benefits from using CAD.

- Other applications of computers include: accounting, marketing, submittals, change orders, payroll, cost control, procurement, materials control, takeoffs, mail, programming, quality control, calculations, design.

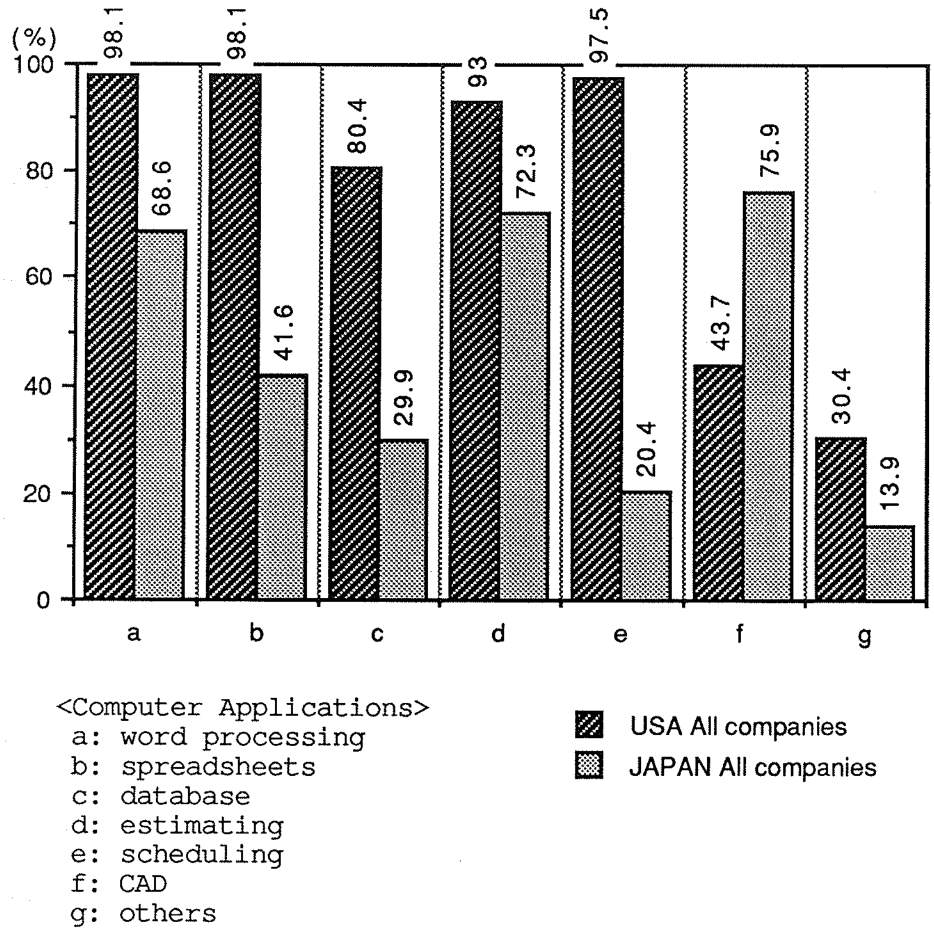
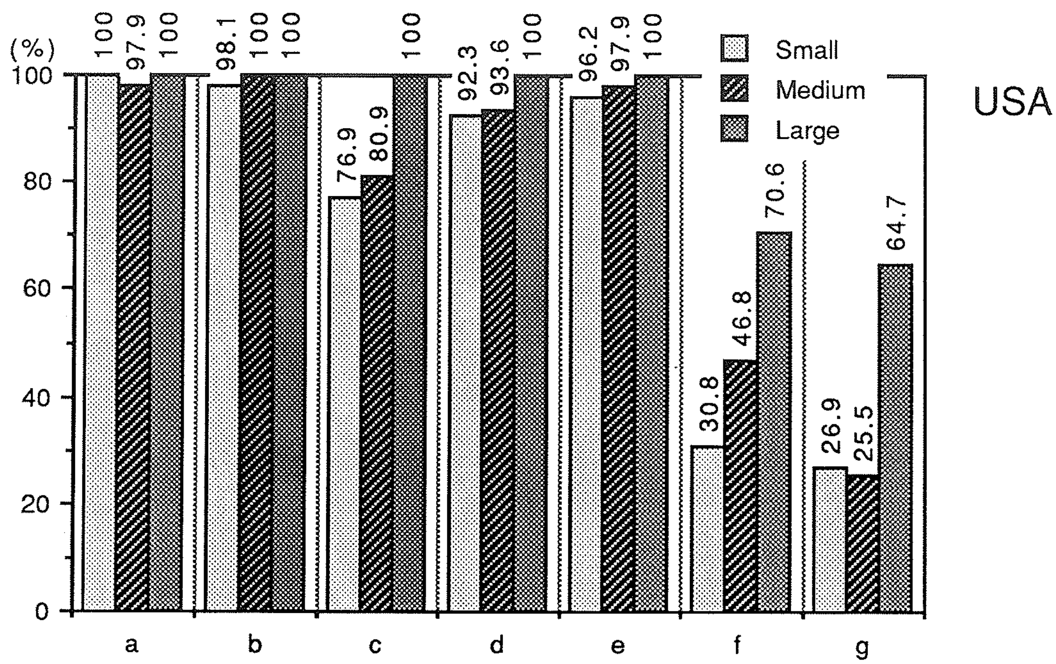
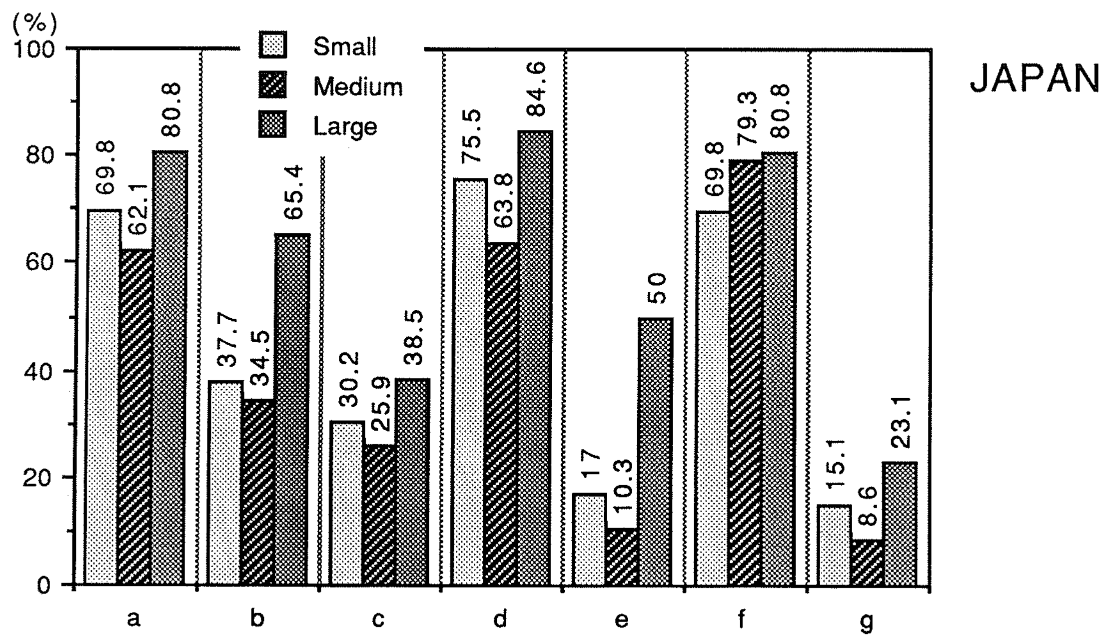


Figure 6 Current Computer Applications on Project Sites (Question 2)

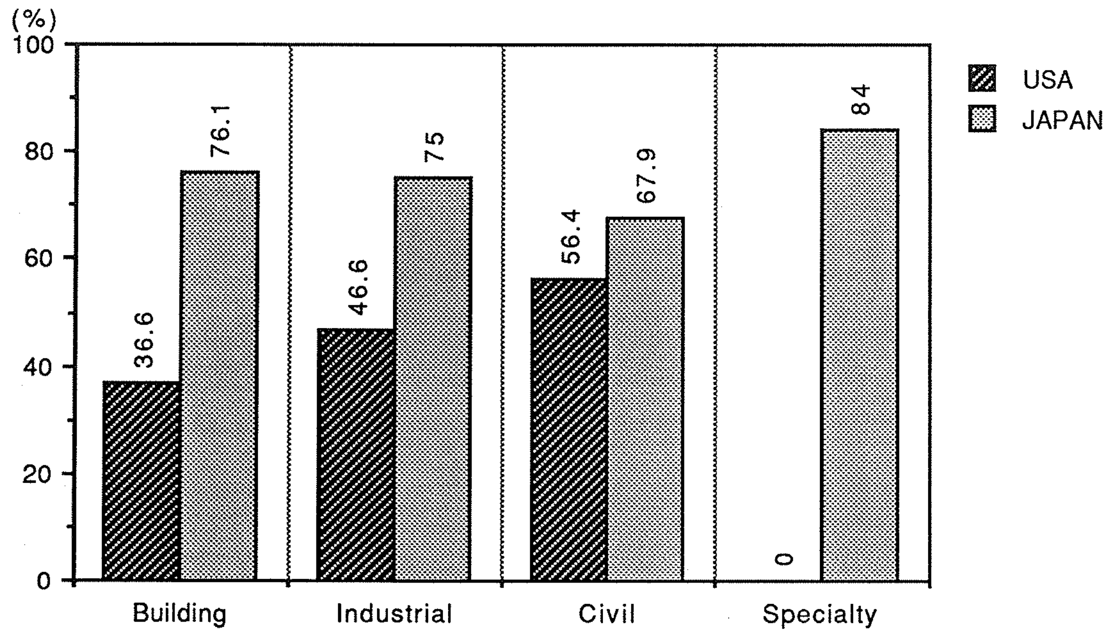




<Computer Applications>
a: word processing
b: spreadsheets
c: database
d: estimating
e: scheduling
f: CAD
g: others

<Notes>
Size of company by annual revenue
Small: $100M - $200M
Medium: $200 - $1,000M
Large: $1,000M -

Figure 7 Current Computer Applications on Project Sites by Size of Company (Question 2)



<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

Figure 8 Percentage of Companies That Use CAD by Type of Company (Question 2)

Findings from Figures 9

Question 3: Computer Literacy on Project Team

Note: Category d added because many respondents indicated that they had some competent operators and some computerphobes.

- Most members of construction project teams have some computer skills in US companies.

- A significant number of US project people are considered very competent with computers.

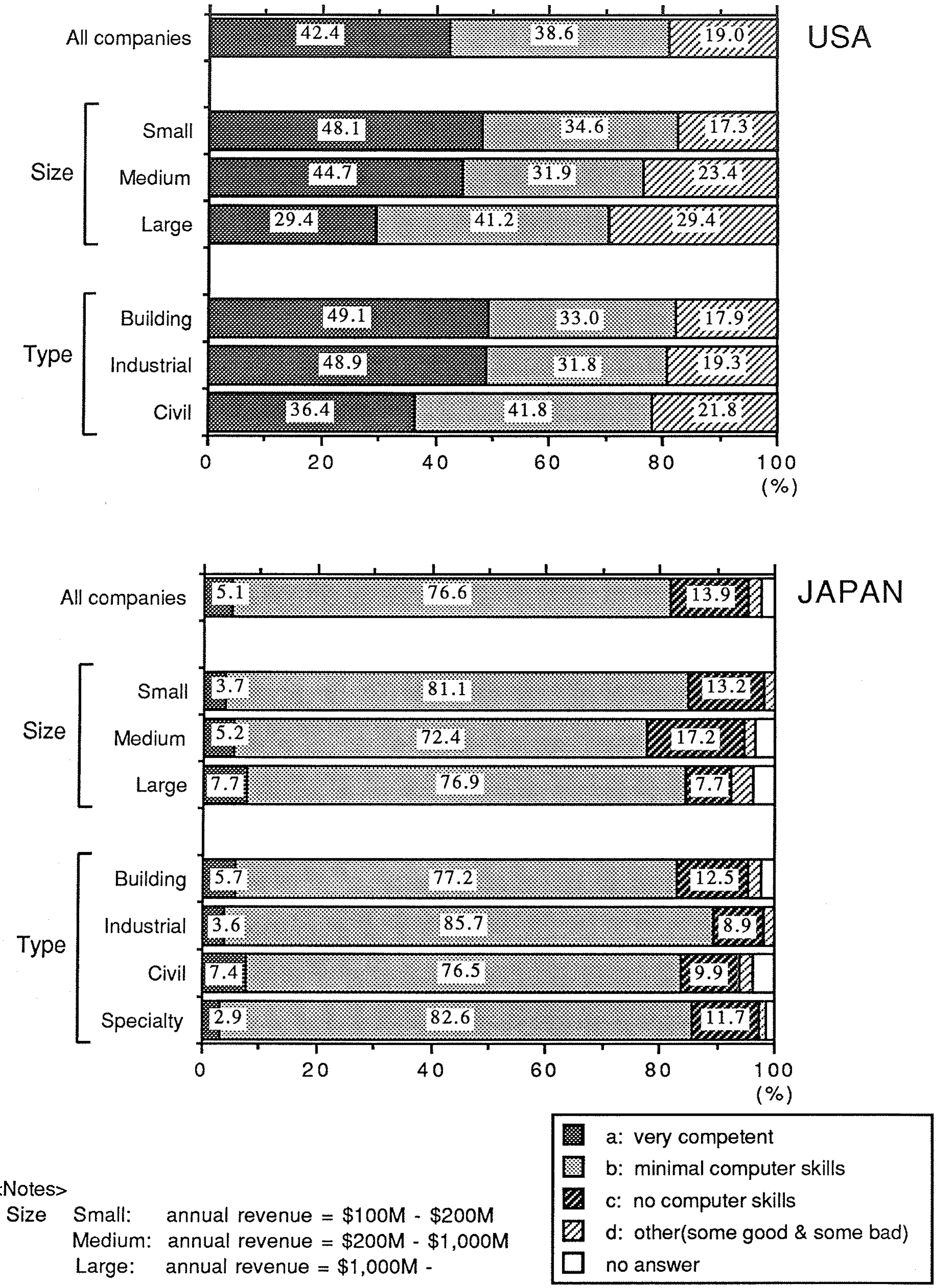
- Small US companies report more people who are very competent with computers than large companies. Perhaps this is because small companies use computers more to leverage their more limited numbers.

- Very few Japanese contractors claim to have people who very competent with computers.

- The vast majority of Japanese companies have some computers skills.

- No difference by size or type of company for Japanese companies.

- More U.S. companies reported very competent people. This may be a cultural difference because Japanese shy away from saying they are excellent or even above average.



<Notes>
- Size Small: annual revenue = $100M - $200M
Medium: annual revenue = $200M - $1,000M
Large: annual revenue = $1,000M -

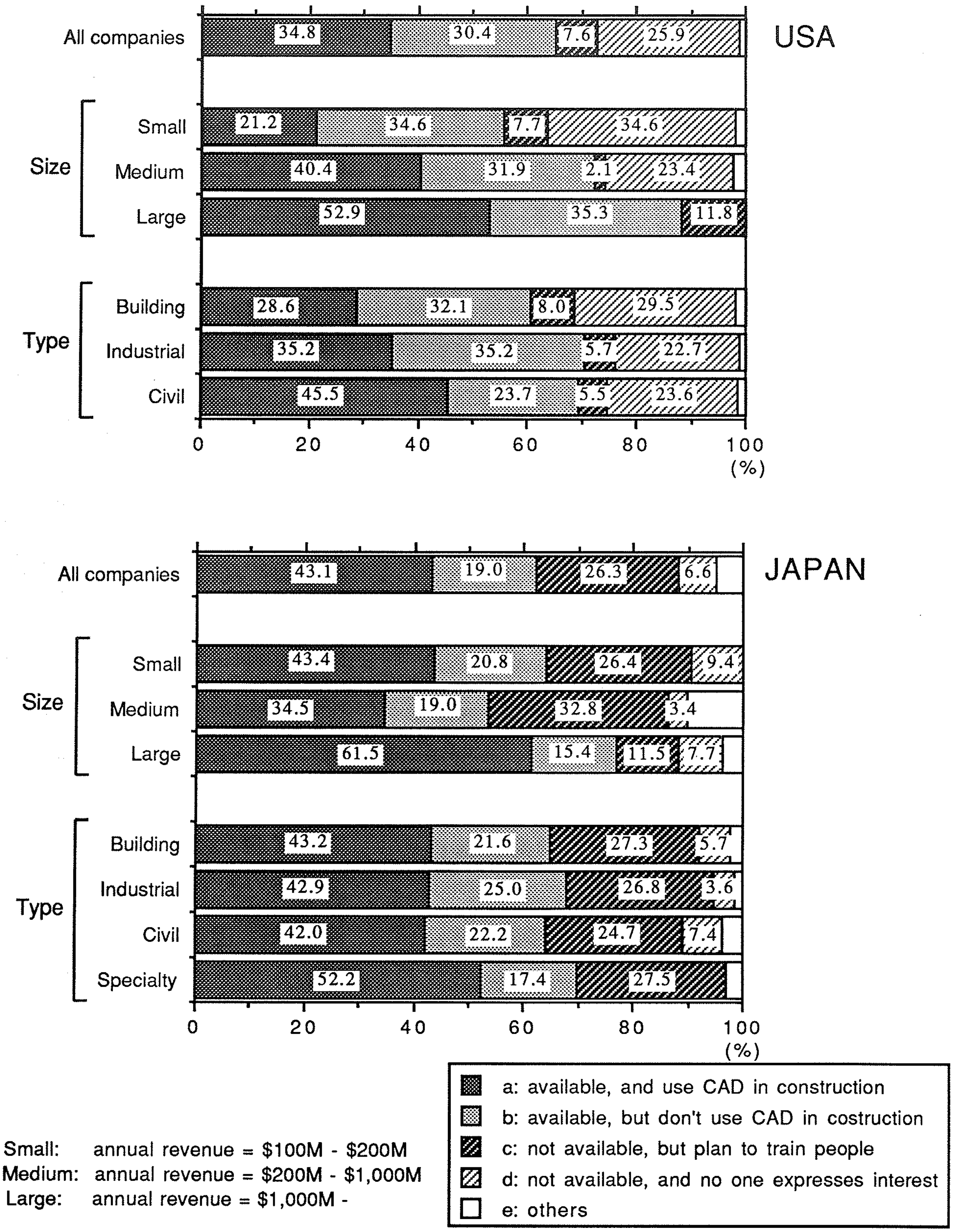
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 9 Computer Literacy of People on Project Teams (Question 3)

Findings from Figure 10

Question 4: Availability of People Who Can Operate CAD

- Larger companies have more people who know how to use CAD.
- A significant number of small US companies, greater than 30%, have no interest in CAD.
- US civil contractors have more people who know how to use CAD than other types of US construction companies.
- All types of US companies had more than 20% that had no interest in CAD.
- Little difference by type of company for Japanese respondents.
- Most Japanese companies at least are interested in CAD, as opposed to U.S. responses which indicate that many companies are not interested in using CAD.
- Most Japanese specialty companies use CAD, from question 2, so naturally they have the largest percentage of people who know how to use CAD.



<Notes>
- Size Small: annual revenue = $100M - $200M
Medium: annual revenue = $200M - $1,000M
Large: annual revenue = $1,000M -

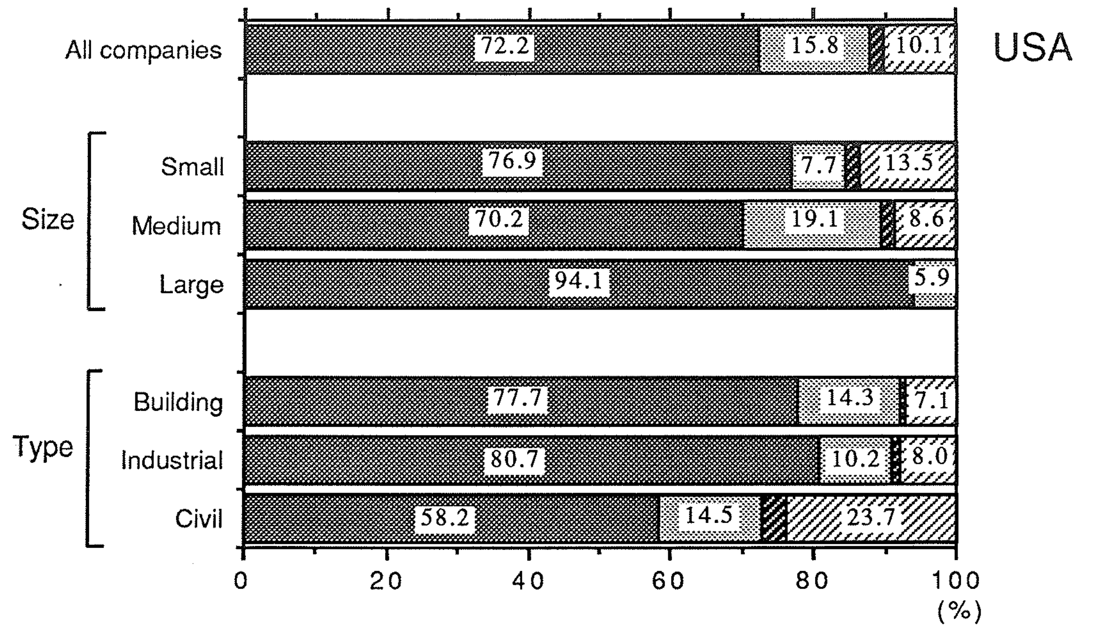
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

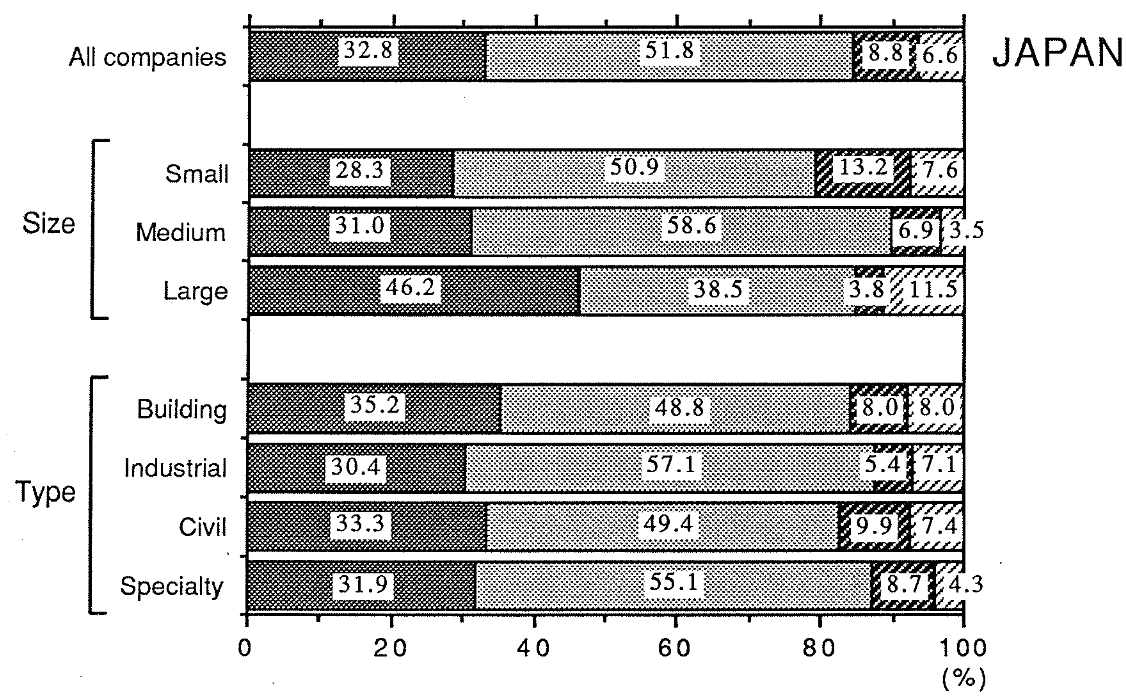
Figure 10 Availavility of People Who Can Operate CAD (Question 4)

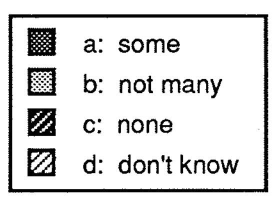
Findings from Figure 11

Question 5: Percentage of Projects Designed Using CAD

- Most US companies think at least some of their projects are designed using CAD
- US civil contractors report the lowest percentage of project designed using CAD but they still use CAD the most.
- Fewer Japanese than U.S.companies said some projects were designed using CAD
- Most Japanese companies said not many of their projects were designed using CAD.







<Notes>

- Size Small: annual revenue = $100M - $200M
  Medium: annual revenue = $200M - $1,000M
  Large: annual revenue = $1,000M -

- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 11 Percentage of Projects Designed by A/E's Using CAD (Question 5)

Findings from Figure 12-13

Questions 6b: Size of Projects Designed Using CAD

Note: The calculation of the responses to this question were combined as follows: companies reporting large and all (regardless of size) projects designed using CAD were included in the first category. Companies reporting all and medium were included in the second category and companies reporting small and all were included in the third category. Totals equal more than 100% because respondents indicated different sized projects designed using CAD.

- More large projects in the US are designed using CAD than in Japan.
- Twice as many large projects in the US are designed using CAD than small projects.
- In Japan, medium sized projects are most often designed using CAD
- No difference by type of company in either country.

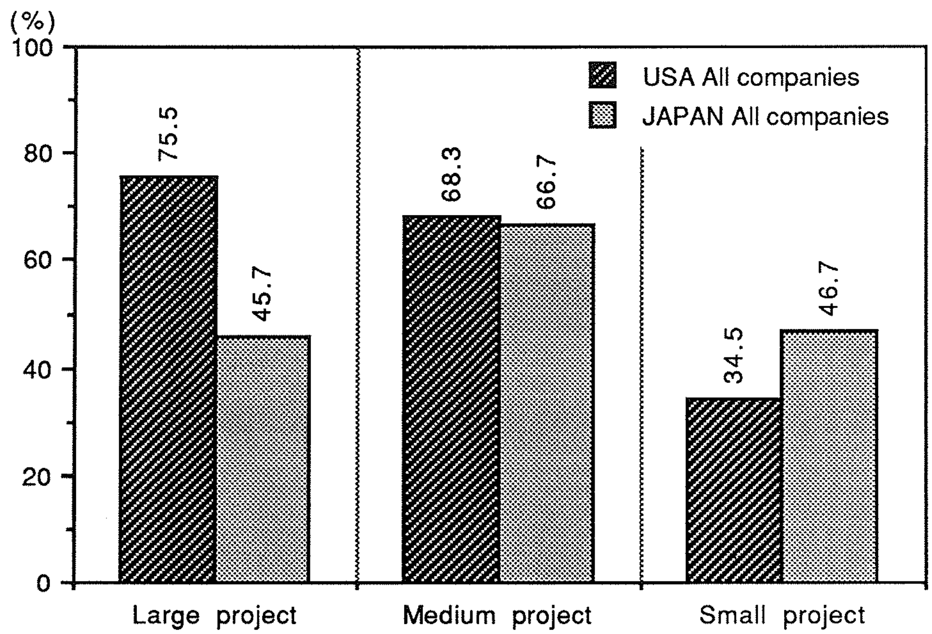
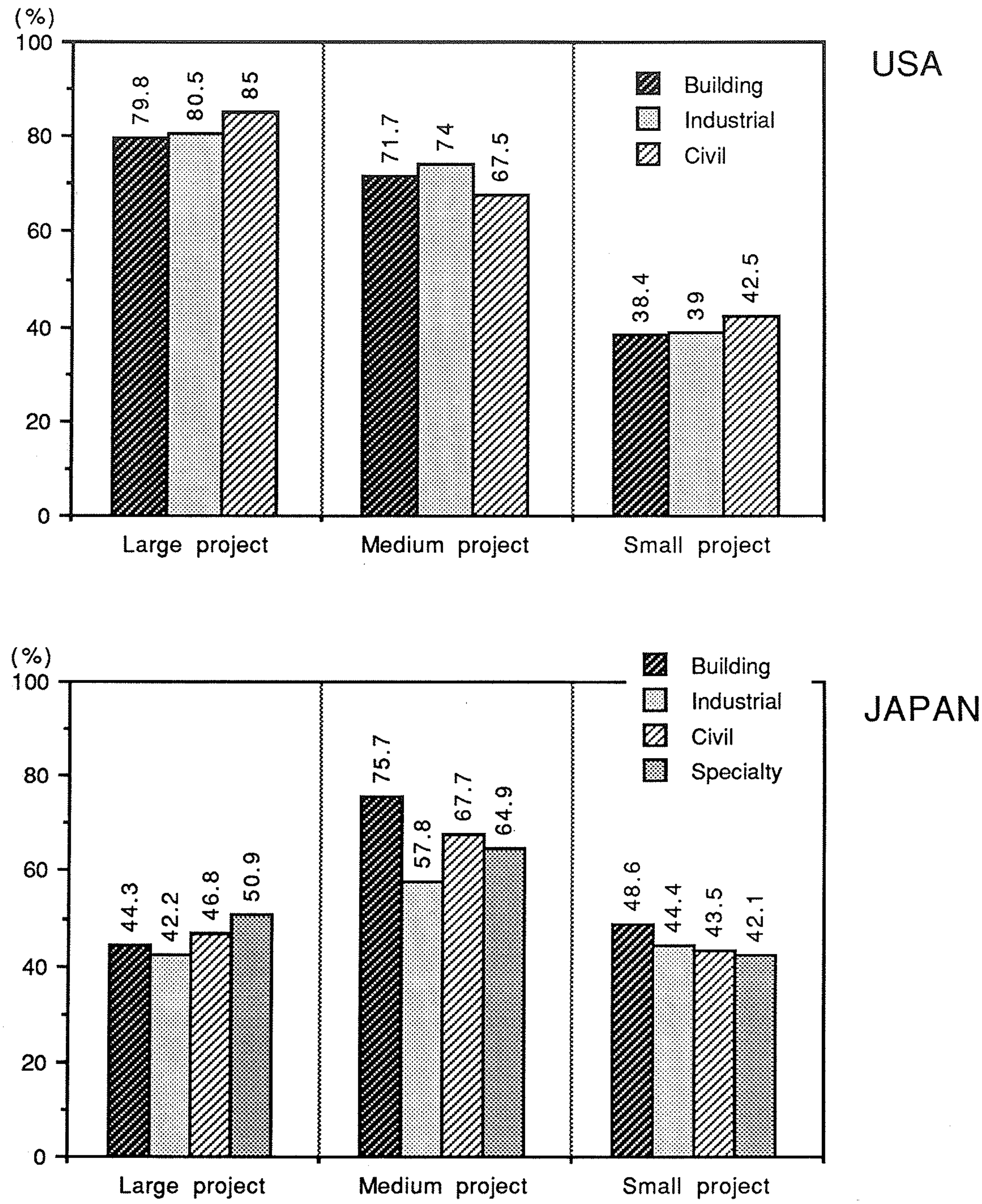


Figure 12 Size of Projects Designed by A/E's Using CAD (Question 6b)



<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

Figure 13 Size of Projects Designed by A/E's Using CAD (by Type of Company) <Question 6b>

Findings from Figure 14-16

Question 6C: Types of CAD used by A/E's for Design

Note: Question 6C considered only companies that indicated that some of their projects were designed using CAD. Totals equal more than 100% because respondents indicated more than one type of project designed using CAD.

- Most companies in both countries use only 2D CAD.
- Few companies in either country understand or use 2.5D CAD.
- Large US companies use 3D CAD more than small or medium companies.
- Almost all small US companies use 2D CAD.
- Large Japanese companies use 3D CAD more than twice as much as small or medium sized Japanese companies.
- No difference by type of company in either country.

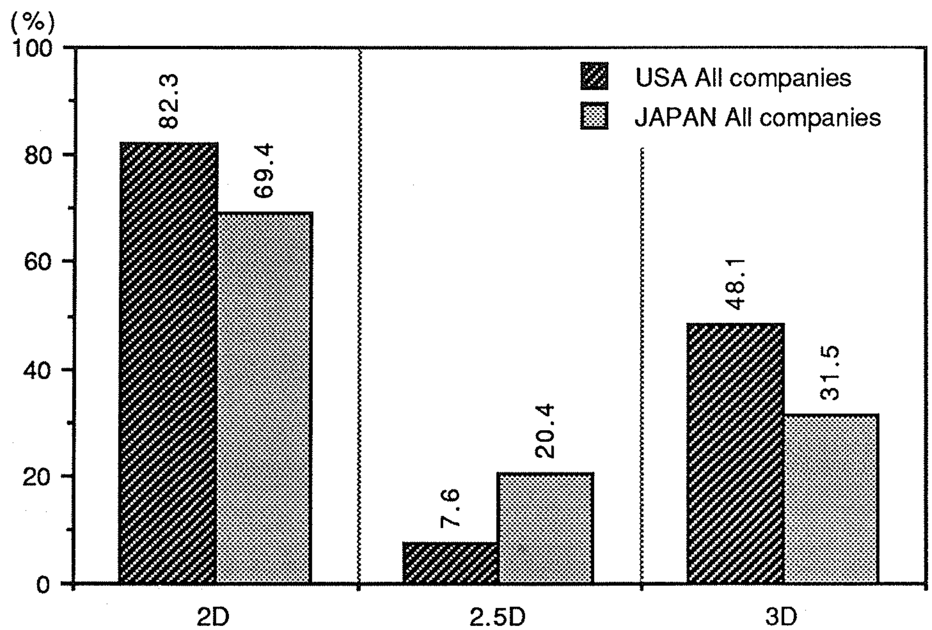
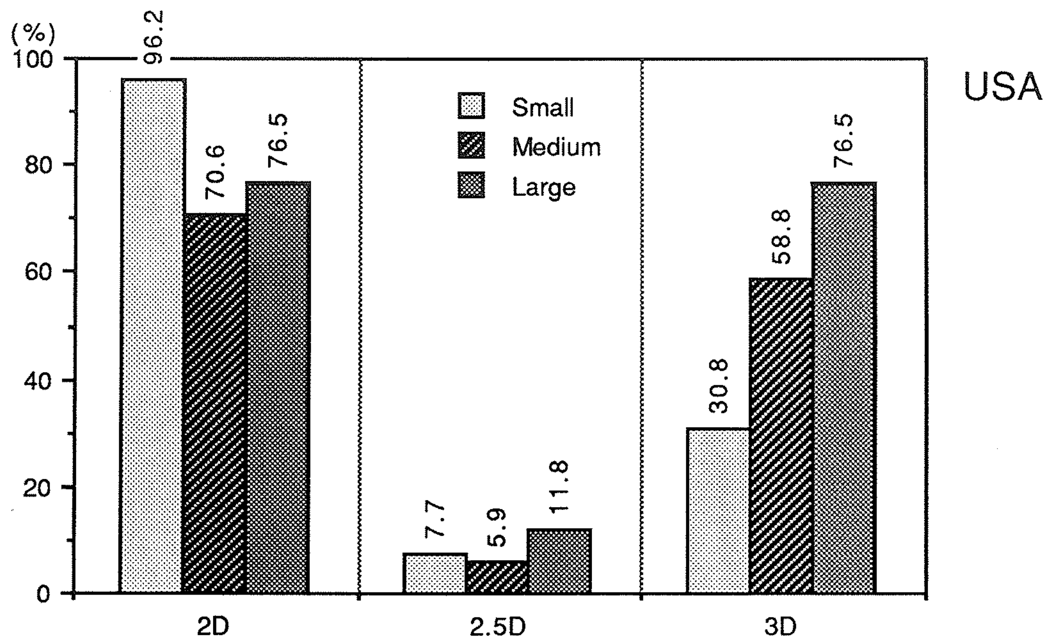
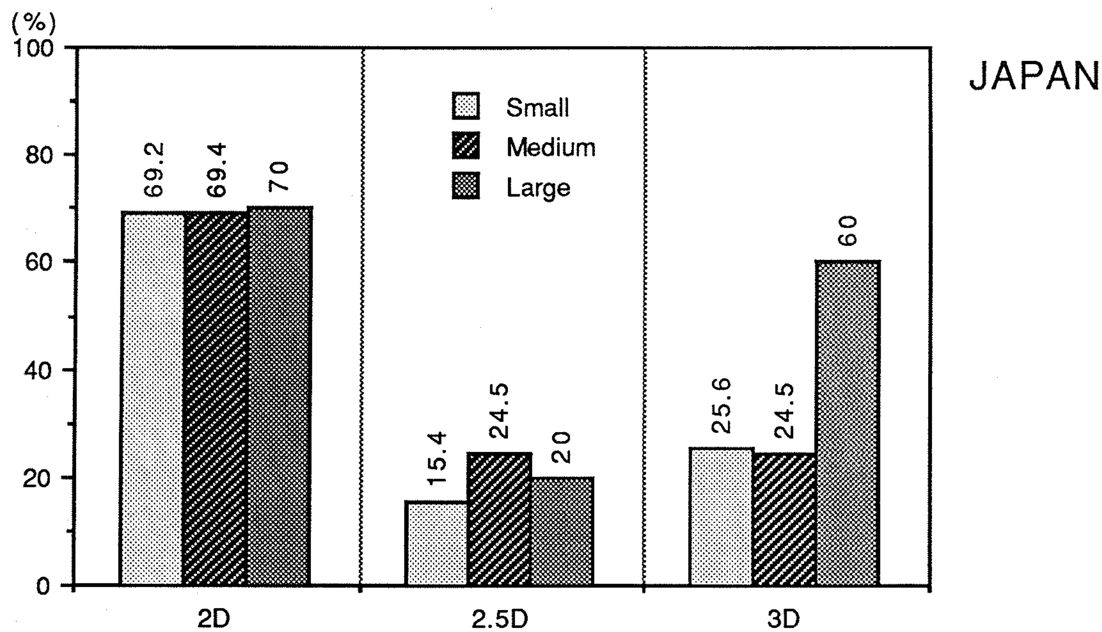


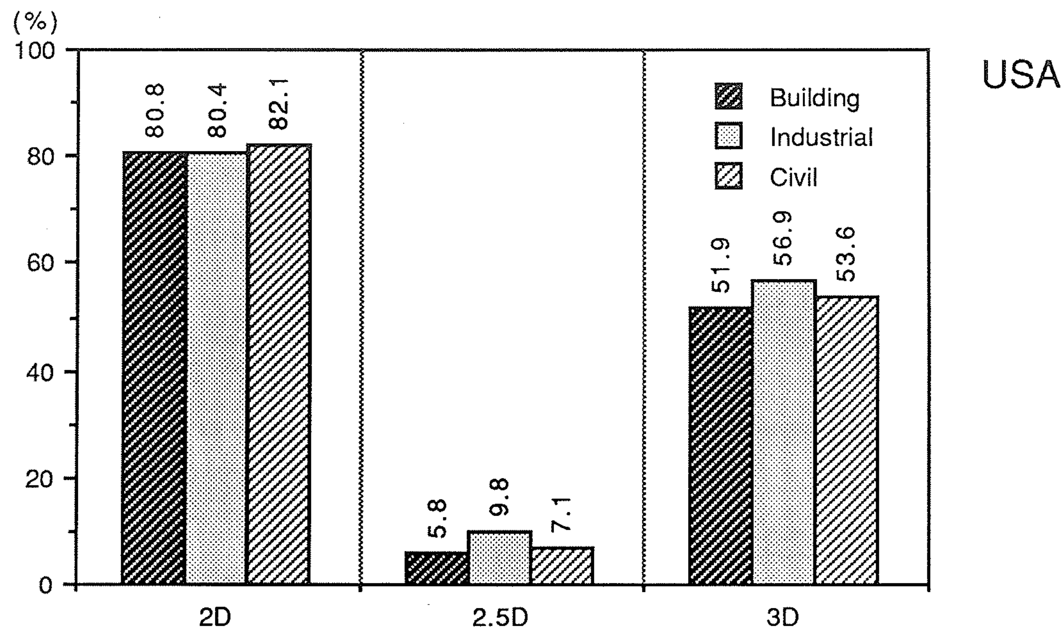
Figure 14 Type of CAD Used by A/E's for Design (Question 6c)

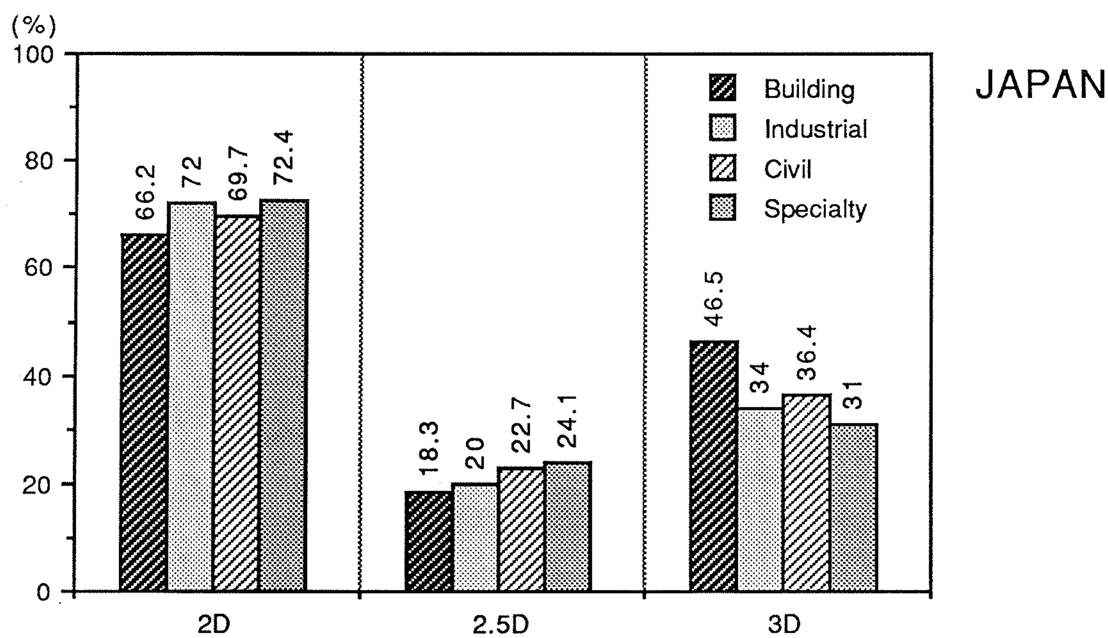




<Note>
Size of company by annual revenue
Small: $100M - $200M
Medium: $200 - $1,000M
Large: $1,000M -

Figure 15 Type of CAD Used by A/E's for Design (by Size of Company) <Question 6c>





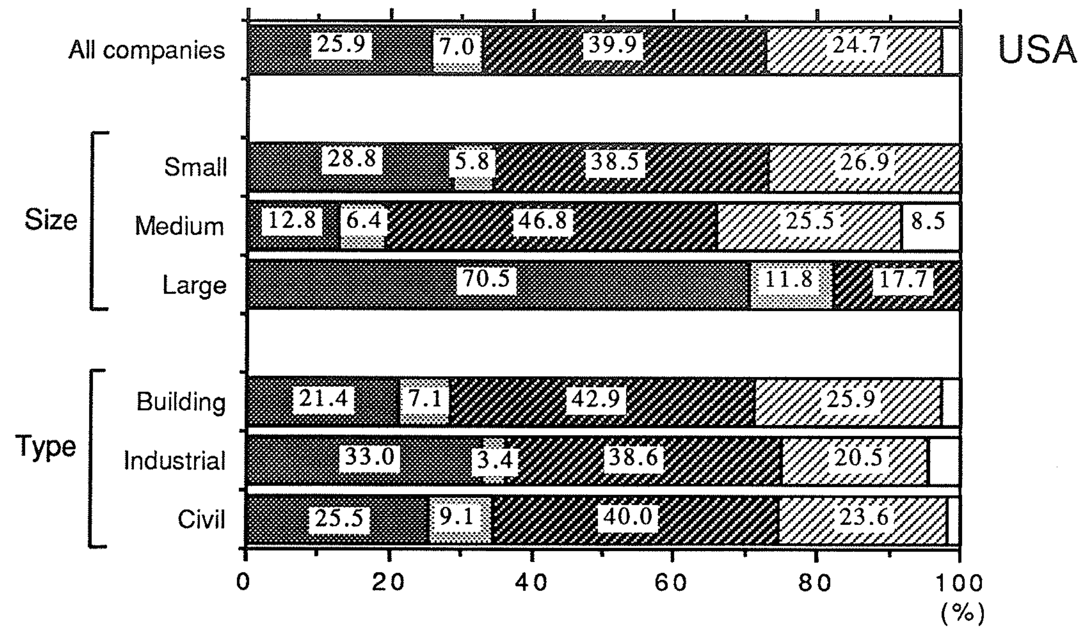
<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

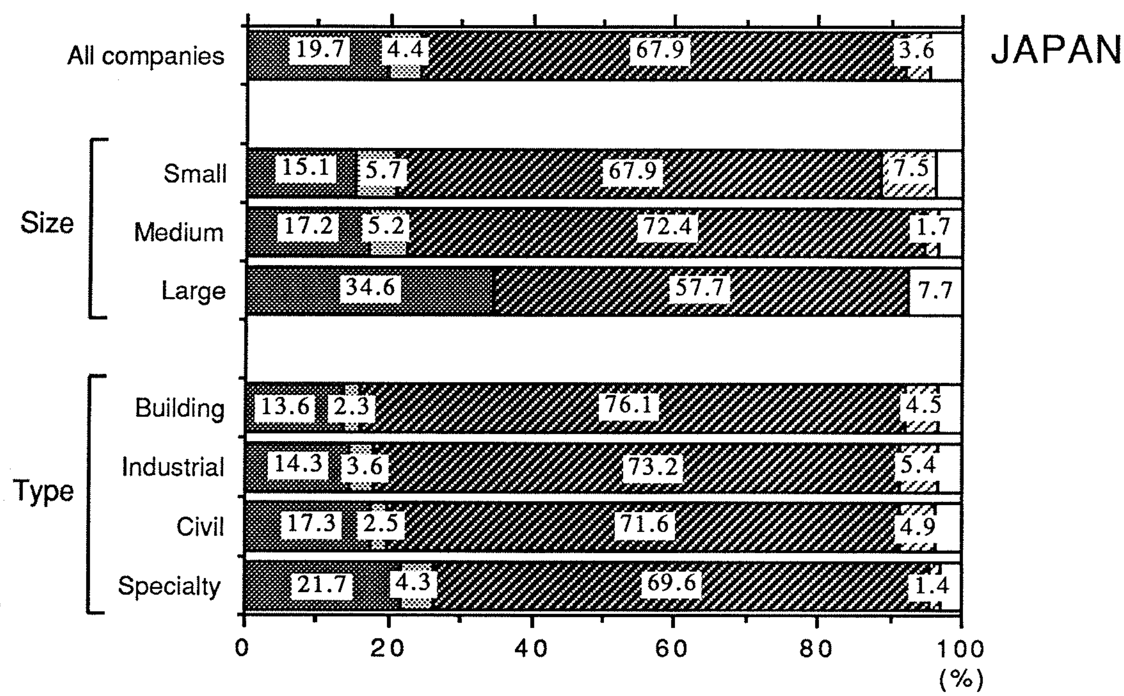
Figure 16 Type of CAD Used by A/E's for Design (by Type of Company) <Question 6c>

Findings from Figure 17

Question 7: Ability to Get Electronic Design Information

- Majority of contractors from both countries have tried or at least are interested.
- No significant difference in interest levels between types of companies in either country.
- A majority of large companies in both countries have received design data electronically and all are at least interested.
- 20% of medium and small US respondents are not interested in getting design information electronically.
- All Japanese companies get electronic design information or are interested in getting it from the A/E.
- Smaller percentage of large Japanese companies than large U.S. companies have received electronic data





- a: have gotten electronic design information
- b: have tried but A/E's did not cooperate
- c: interested but have not tried
- d: not interested
- no answer

<Notes>

- Size
  - Small: annual revenue = $100M - $200M
  - Medium: annual revenue = $200M - $1,000M
  - Large: annual revenue = $1,000M -
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 17 Ability to Get Electronic Design Information from A/E's (Question 7)

Findings From Figure 18

Question 8: Use of CAD to Design Temporary Structures

- Twice as many US civil contractors use CAD for temporary structures as others.

- The majority of US respondents has even considered using CAD for temporary structures.

- Twice as many large US companies as small ones use CAD for temporary structures.

- The vast majority of US respondents believe that it would at least be a good idea.

- The majority of large Japanese companies use CAD for temporary structures

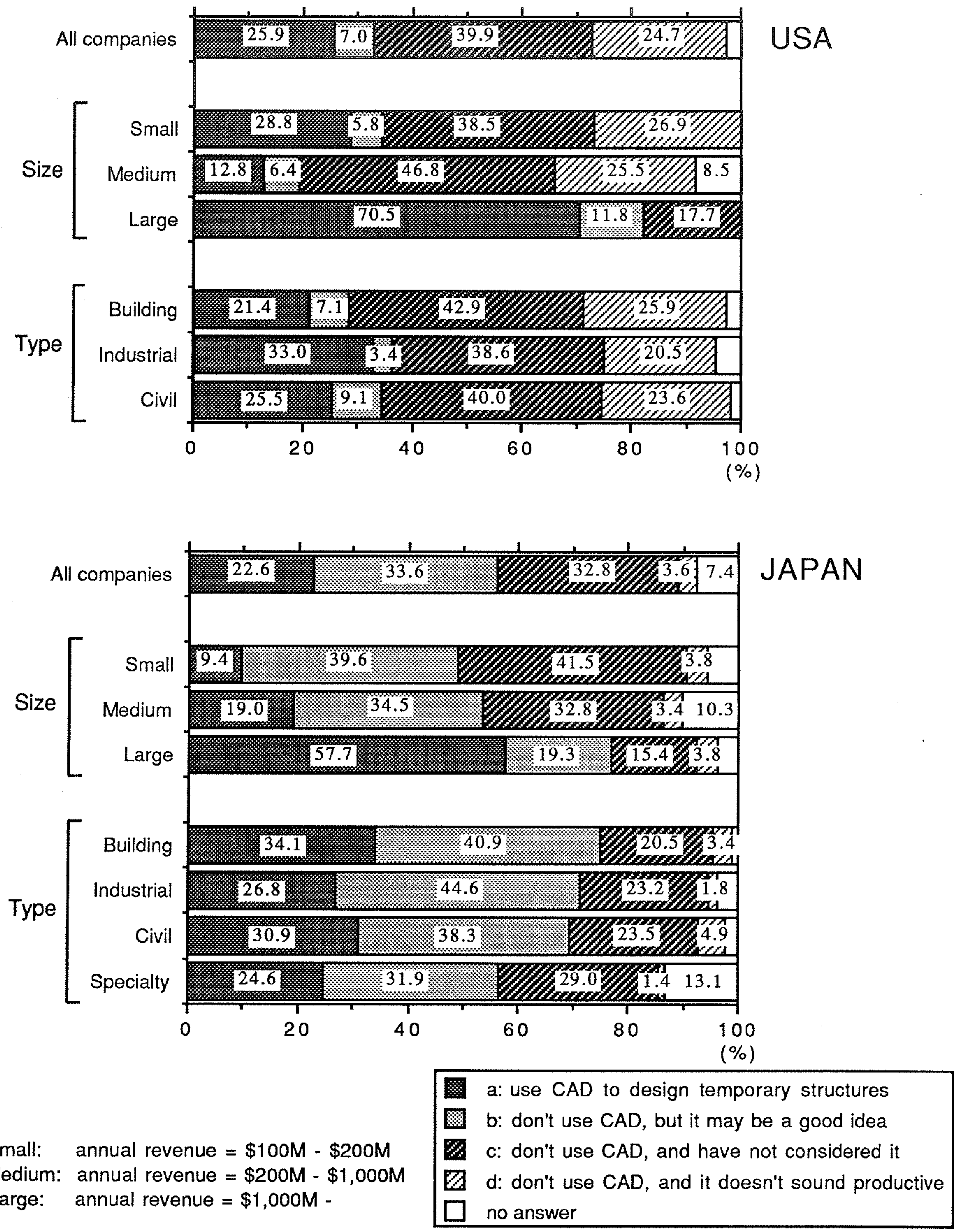
- A significant percentage of Japanese respondents have not even considered using CAD for temporary structures.

- Little difference by type of Japanese company

- Larger percentages of building and industrial companies from Japan used CAD for temporary structures than in the U.S.

- Japanese specialty companies, which reported using CAD the most, use it least for temporary structures perhaps because they use temporary structures the least.

- Both US and Japanese companies report using CAD to design scaffolding, rigging, cofferdams, formwork, falsework, excavation supports, retaining walls, temporary structures and shoring. They also use CAD to plan site layouts and check clearances. Other companies identified the same areas as potential applications of CAD that they have not explored.



<Notes>

- Size Small: annual revenue = $100M - $200M
  Medium: annual revenue = $200M - $1,000M
  Large: annual revenue = $1,000M -
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 18 Use of CAD to Design Temporary Structures (Question 8)

Findings from Figure 19

Question 9: Use of CAD for Shop Drawings

- Most US companies indicated that they do not prepare shop drawings. Since the majority of the respondents were building or industrial constructors, we assume that this is because they have subcontractor who prepare them.

- A significant percentage of the US respondents indicated that they do use CAD for shop drawings.

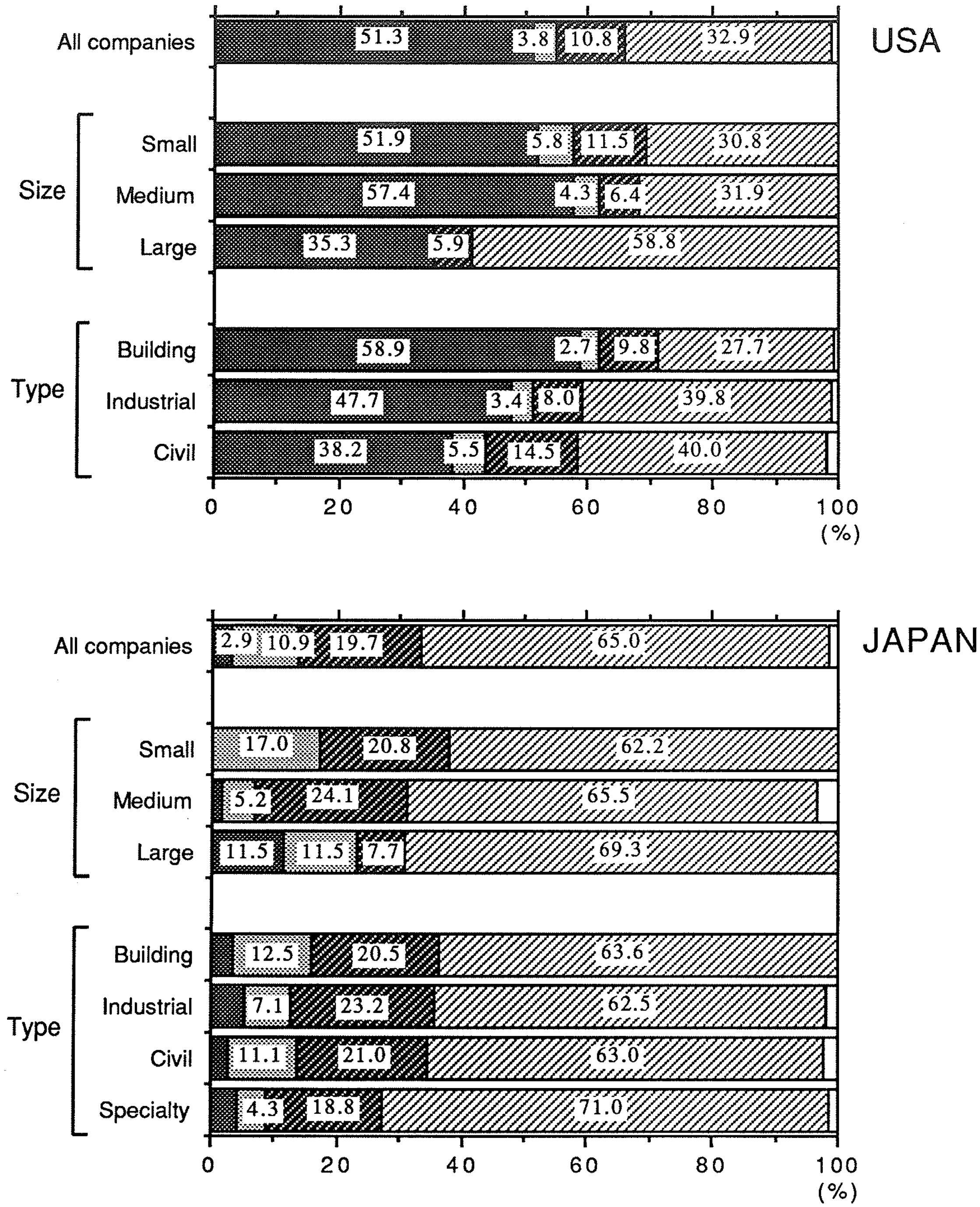
- A majority of large US companies do use CAD for shop drawings.

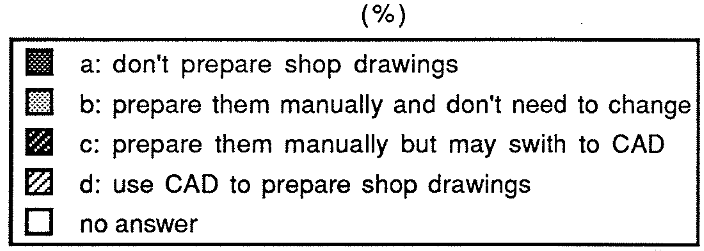
- Very few US companies think that preparing shop drawings manually is efficient, even it they don't prepare shop drawings themselves.

- Most Japanese companies use CAD for shop drawings.

- Little difference by size or type of company of Japanese companies.

- More Japanese companies than U.S. companies use CAD for shop drawings.





<Notes>
- Size Small: annual revenue = $100M - $200M
  Medium: annual revenue = $200M - $1,000M
  Large: annual revenue = $1,000M -
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

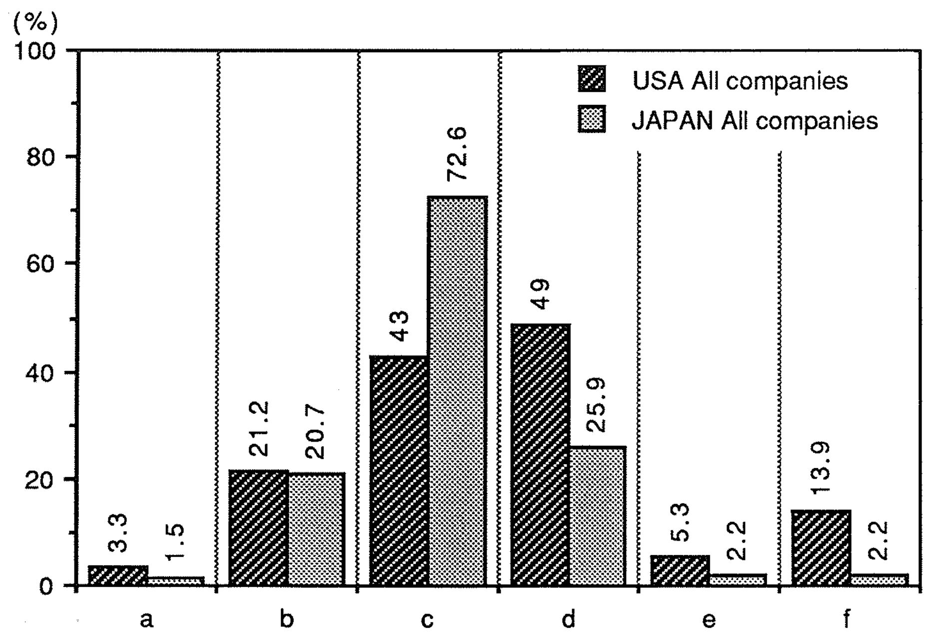
Figure 19 Use of CAD to Prepare Shop Drawings (Question 9)

Findings from Figure 20-22

Question 11: Communication with A/E

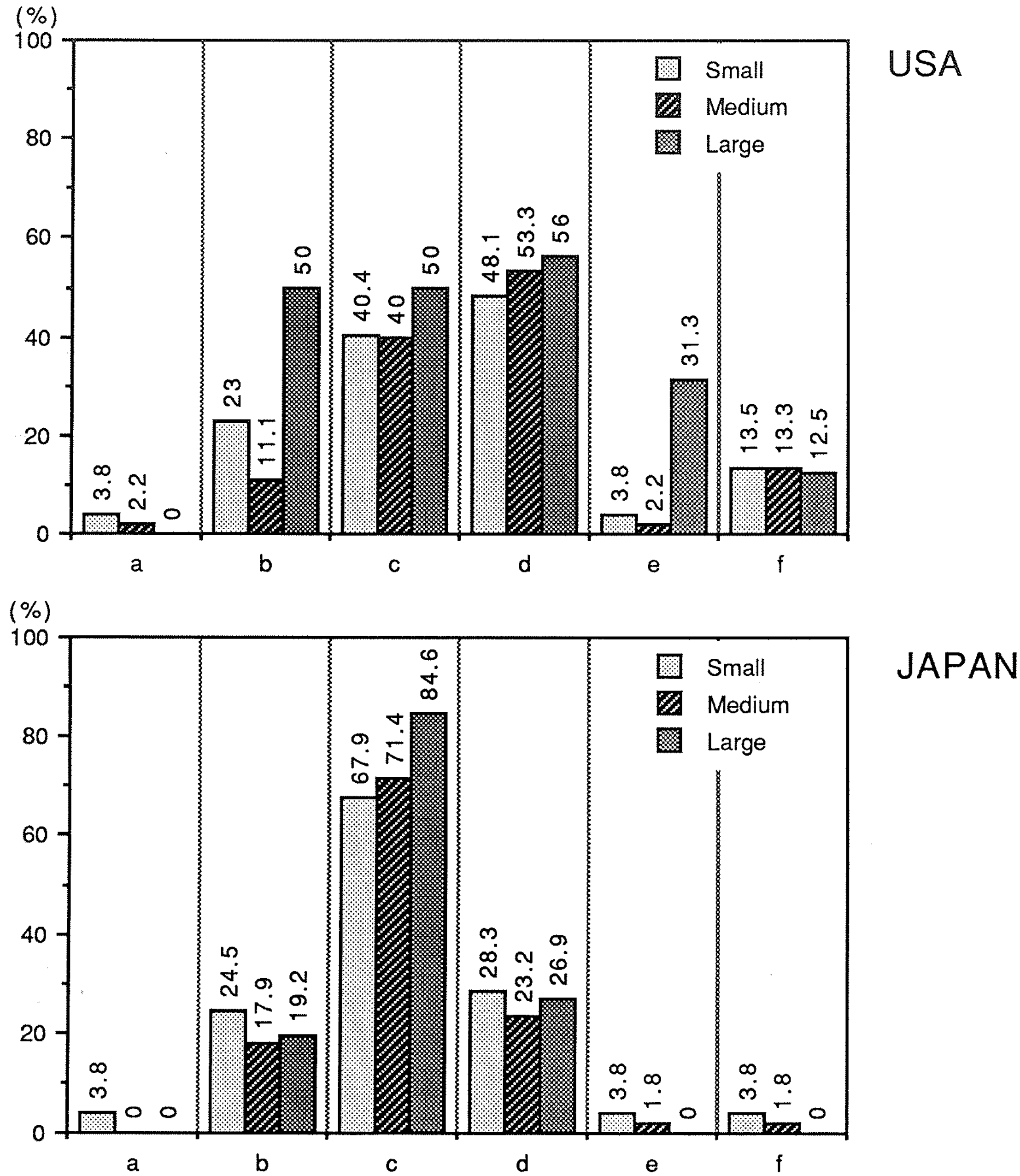
Notes: Totals equal more than 100% because companies communicate with A/E's in many ways. Category f was added because many respondents added category for mail communication.

- In U.S. the fax has become the dominant means of communication while in Japan most companies communicate in person with their A/E's.
- All companies need to communicate with the A/E during construction.
- Little difference by type of company.
- Very little communication takes place using computers and modems in either country.
- Large US companies communicate more by phone and modem than small or medium sized US companies.
- Little difference by size in Japan.



<Communication Method>
a: usually don't need to communicate with A/E's
b: mostly by telephone
c: mostly in person
d: mostly with FAXed information
e: via computers with modems
f: other (by mail)

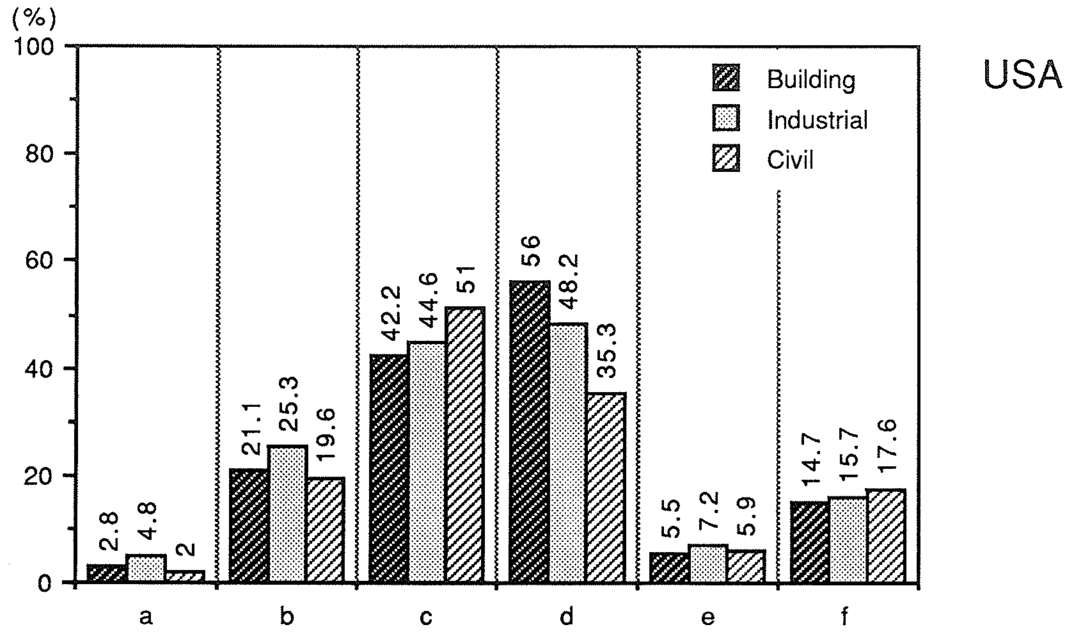
Figure 20 Method of Communicating Change Orders with A/E's (Question 11)

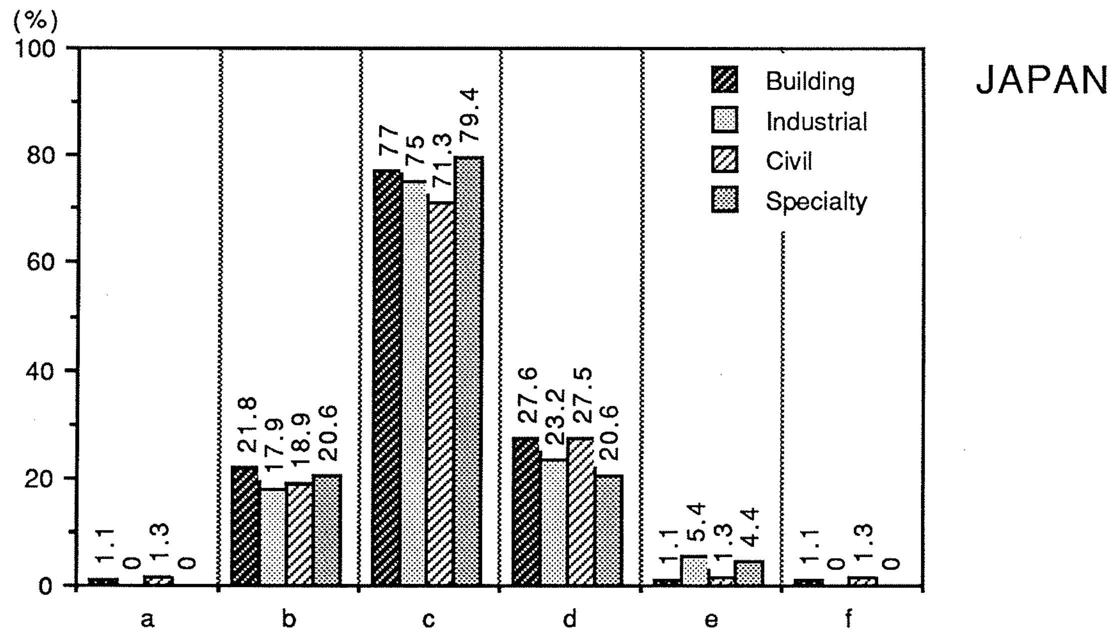


<Communication Method>
a: usually don't need to communicate with A/E's
b: mostly by telephone
c: mostly in person
d: mostly with FAXed information
e: via computers with modems
f: other (by mail)

<Notes>
Size of company by annual revenue
Small: $100M - $200M
Medium: $200M - $1,000M
Large: $1,000M -

Figure 21 Method of Communicating Change Orders with A/E's by Size of Company (Question 11)





<Communication Method>
- a: usually don't need to communicate with A/E's
- b: mostly by telephone
- c: mostly in person
- d: mostly with FAXed information
- e: via computers with modems
- f: other (by mail)

<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

Figure 22 Method of Communicating Change Orders with A/E's by Type of Company (Question 11)

Findings from Figure 23-24

Question 12: Potential of CAD to Improve Construction Operations

- Most small and medium US companies think that CAD will only help construction "some."

- Most large US companies think that CAD will help construction "alot"

- 20% of US respondents do not know whether or not CAD can help construction.

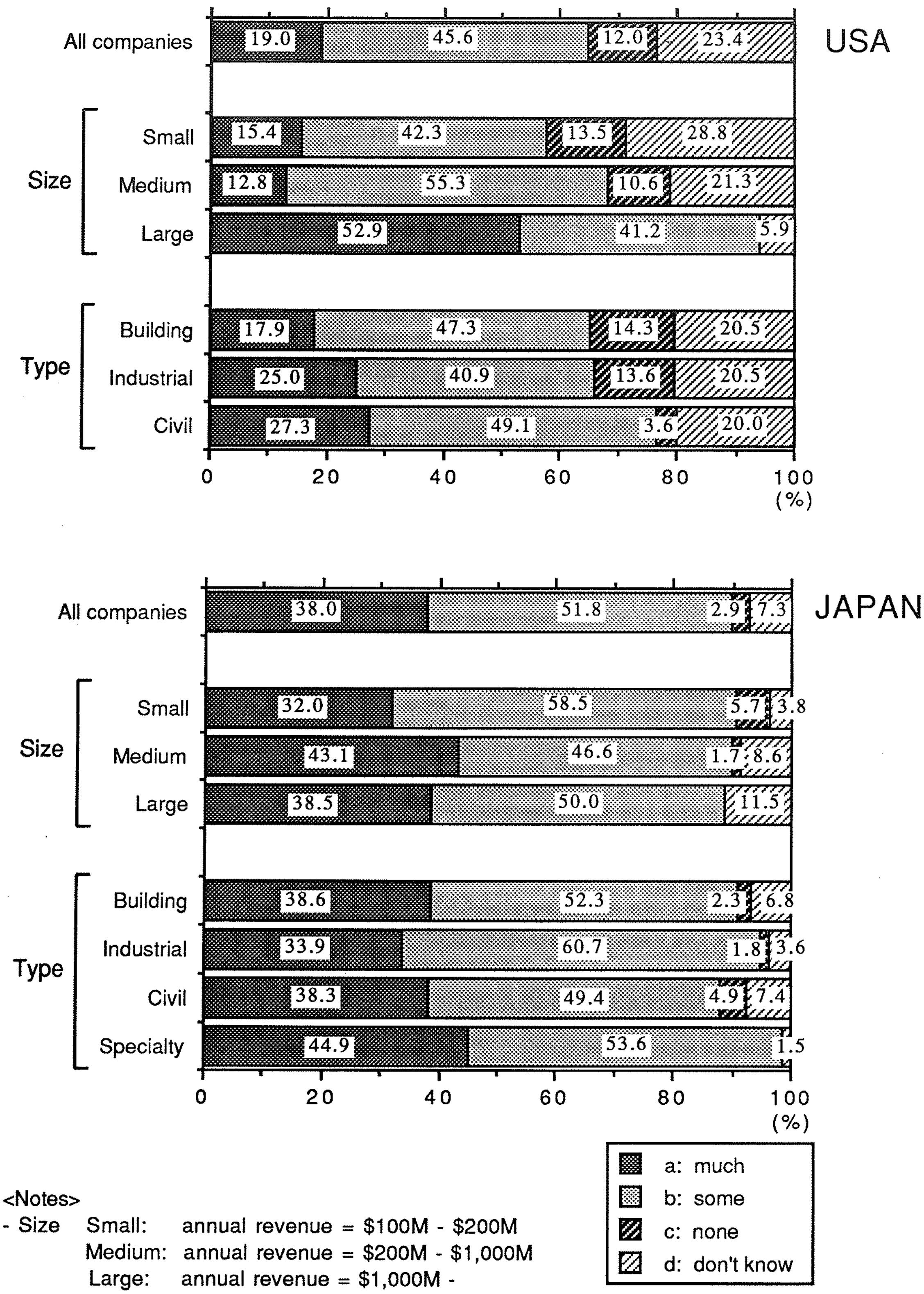
- Little difference by size or type in Japan.

- More Japanese companies than U.S. companies think that CAD will be helpful to construction.

- The vast majority of Japanese companies see "some" value in using CAD in construction.

- Fewer Japanese companies see no value in using CAD in construction than U.S. companies.

- In both U.S and Japan, companies that use CAD see more value in using CAD to support construction than companies that do not use CAD



<Notes>

- Size Small: annual revenue = $100M - $200M
  Medium: annual revenue = $200M - $1,000M
  Large: annual revenue = $1,000M -

- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent

Figure 23 Potential of CAD to Improve Construction Operations (Question 12)

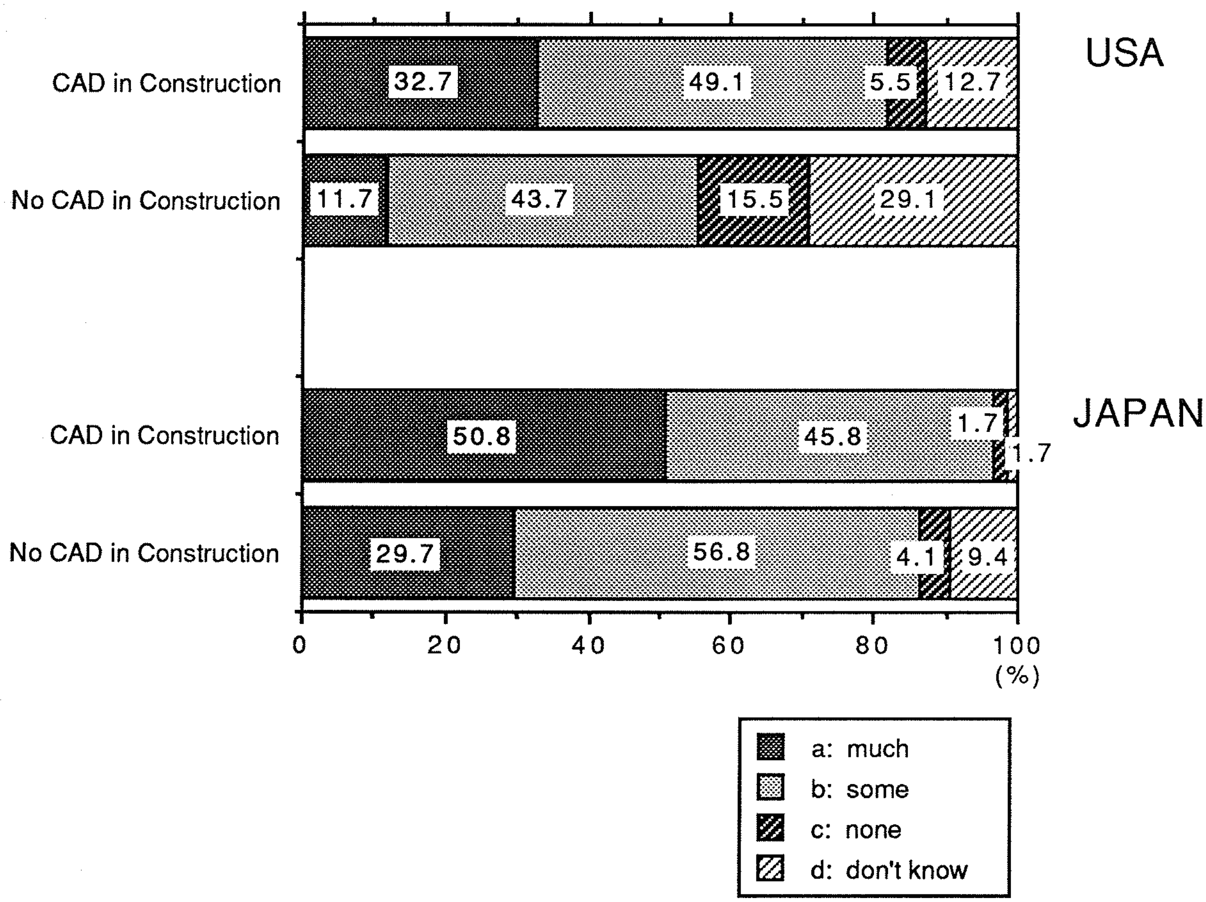


Figure 24 **Potential of CAD to Improve Construction Operations by Comparison between Companies That Use CAD & Don't Use CAD in Construction (Question 12)**

Findings from Figure 25-28

Question 13: Possible CAD Applications in Construction

Notes: Totals equal more than 100% because respondents agreed with more than one of the suggested applications. This questions considered only those who indicated in question 12 that they think that CAD helps construction "alot" or "some." Suggestions offered to help people think how CAD can be used in construction.

- Little difference between responses from U.S. and Japan.

- Few companies pump concrete or use robots so these responses received little positive response.

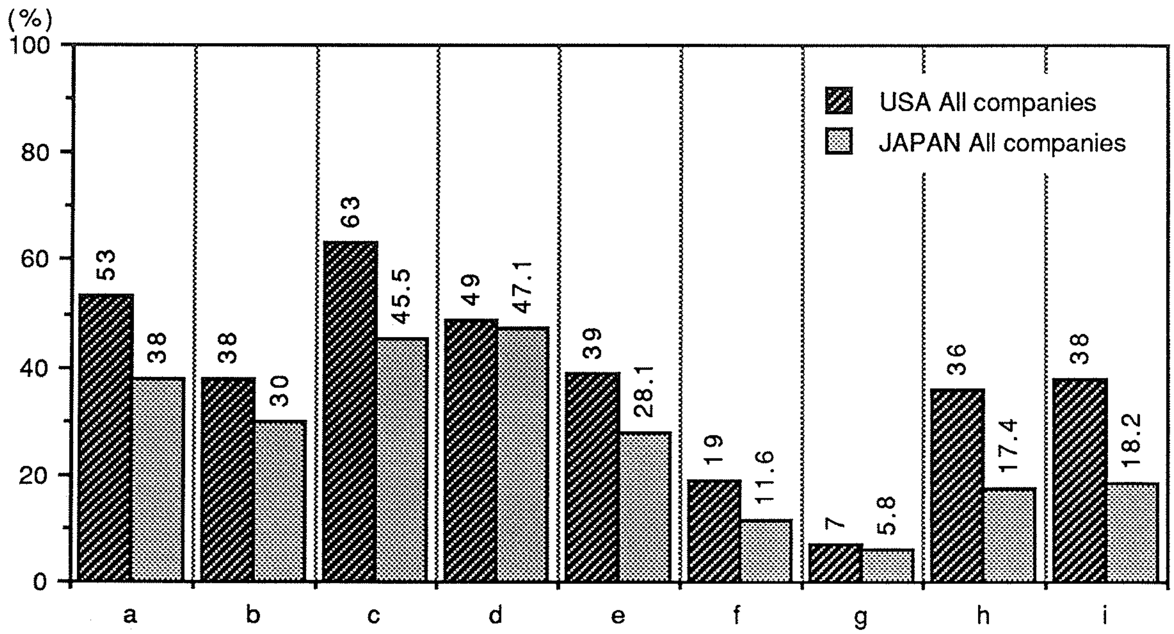
- More large US companies than small or medium thought that any of the suggestions would be beneficial.

- Except for c & e in Figure 26, respondents from Japanese companies of different sizes agreed about the value of the suggested applications of CAD.

- For b in Figure 27, only US civil contractors prepare lift drawings so naturally they saw the most value in that application.

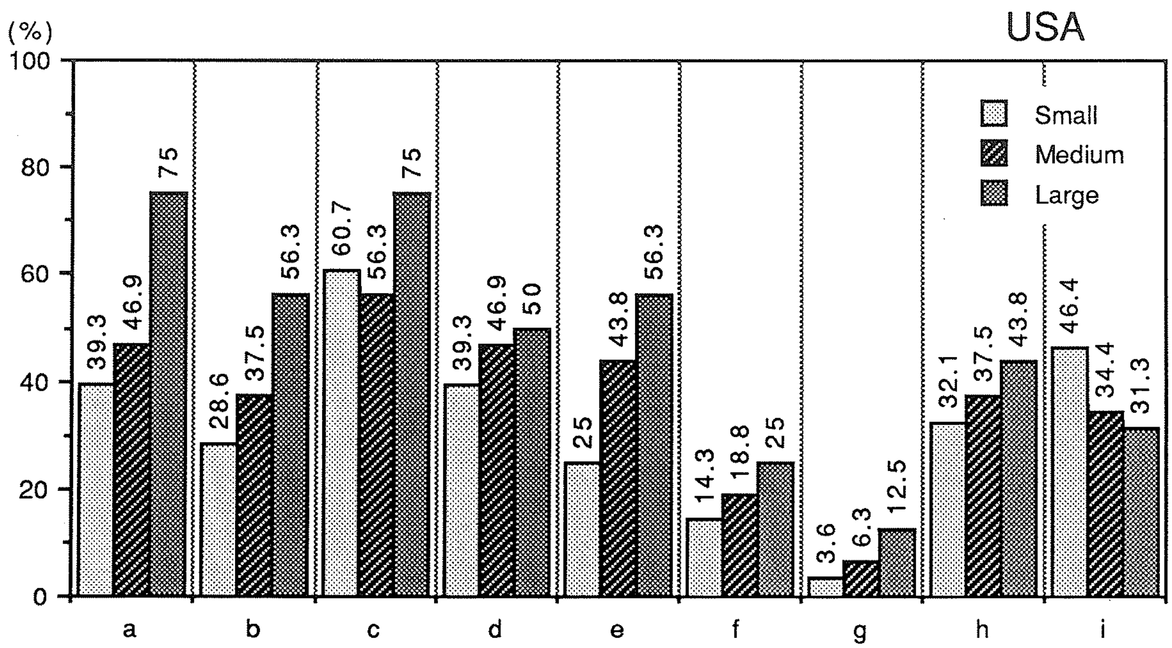
- Little difference between different types of Japanese companies.

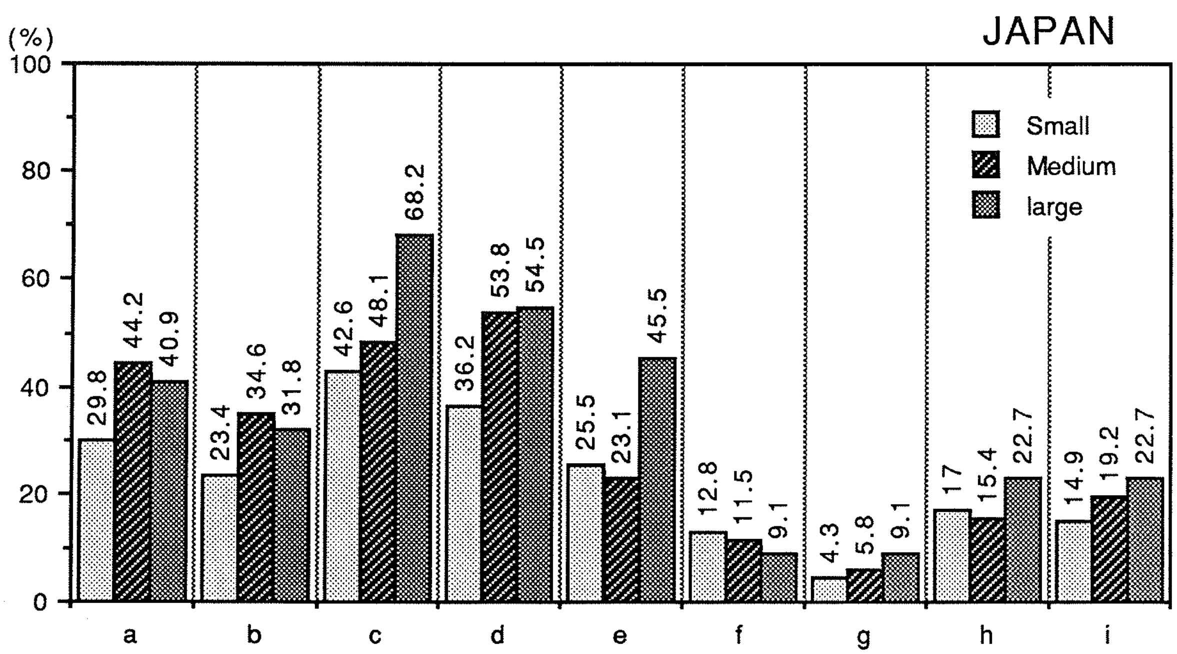
- US and Japanese respondents agreed on other possible applications of CAD in construction. These include estimating, RFI's, value engineering, cost and craft planning, sequence and access planning and construction coordination. Many companies suggested "new" applications that other companies already perform using CAD.



<Construction Operations>
a: coordinate work space
b: prepare concrete lift drawing
c: track as-built drawing
d: monitor and control site layout
e: analyze crane and forklift use
f: planning concrete pumping operations
g: robot control
h: survey control
i: others

Figure 25 Possible CAD Applications in Construction Operations (Question 13)





<Construction Operations>

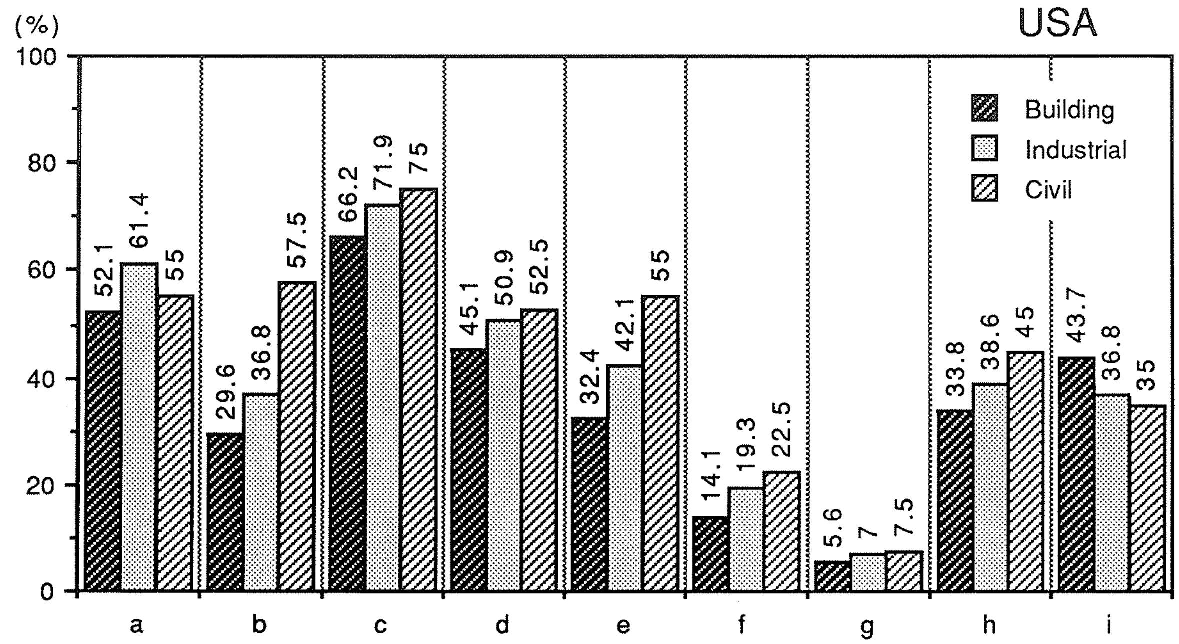
a: coordinate work space
b: prepare concrete lift drawing
c: track as-built drawing
d: monitor and control site layout
e: analyze crane and forklift use
f: planning concrete pumping operations
g: robot control
h: survey control
i: others

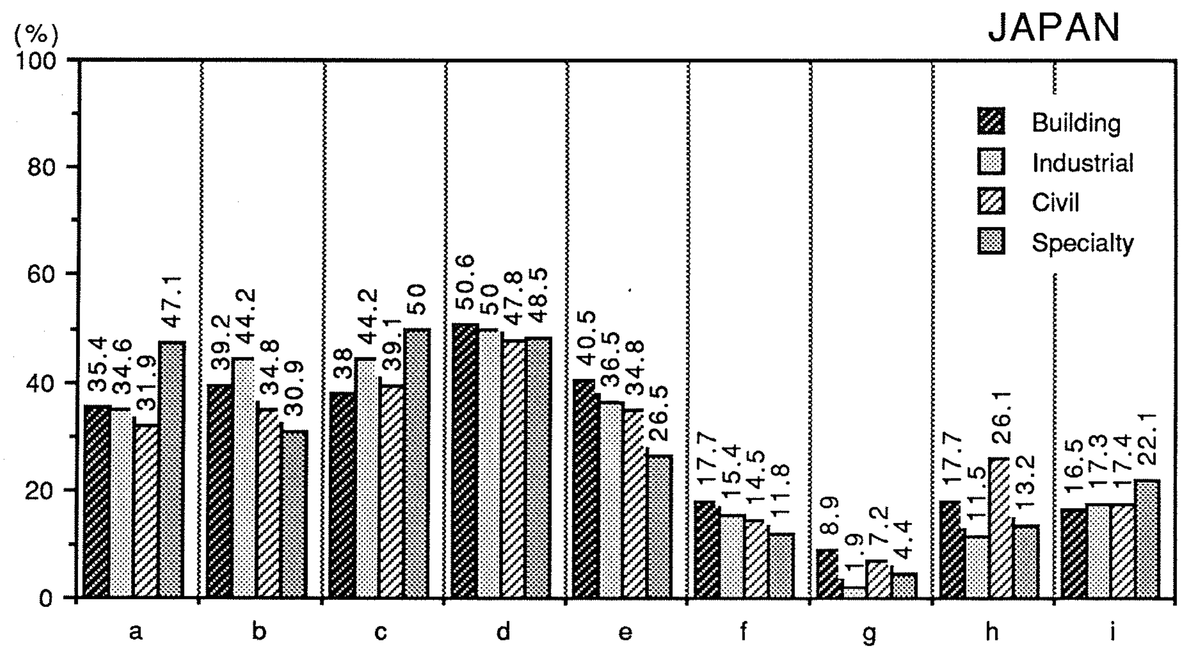
<Notes>

Size of company by annual revenue

Small:	\$100M - \$200M
Medium:	\$200M - \$1,000M
Large:	\$1,000M -

Figure 26 Possible CAD Applications in Construction Operations by Size of Company (Question 13)

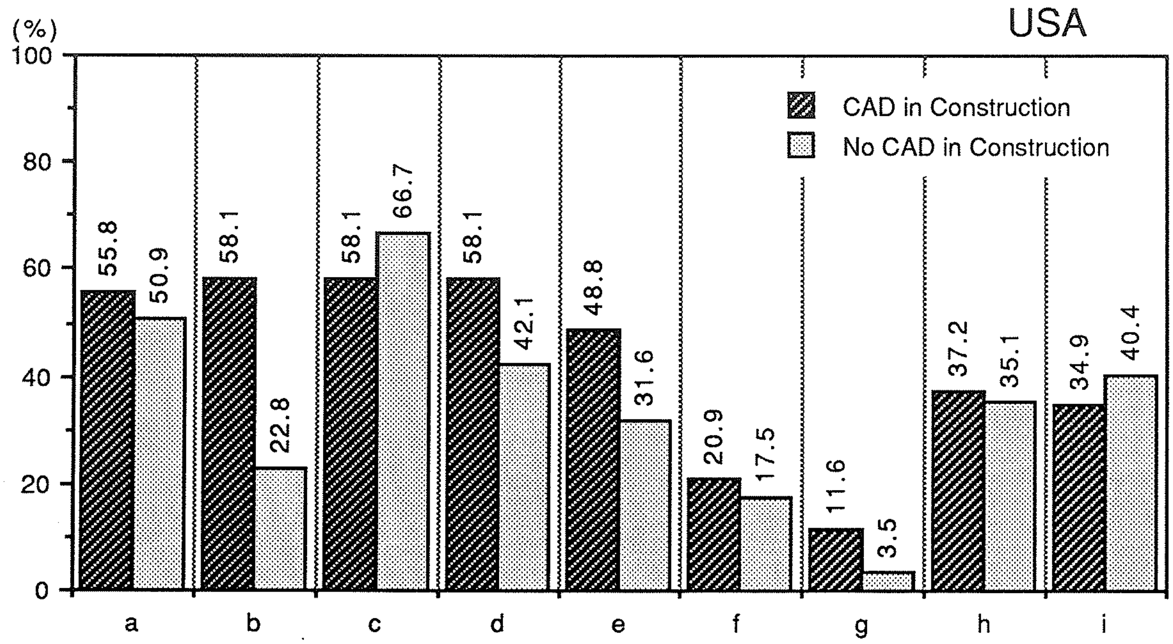


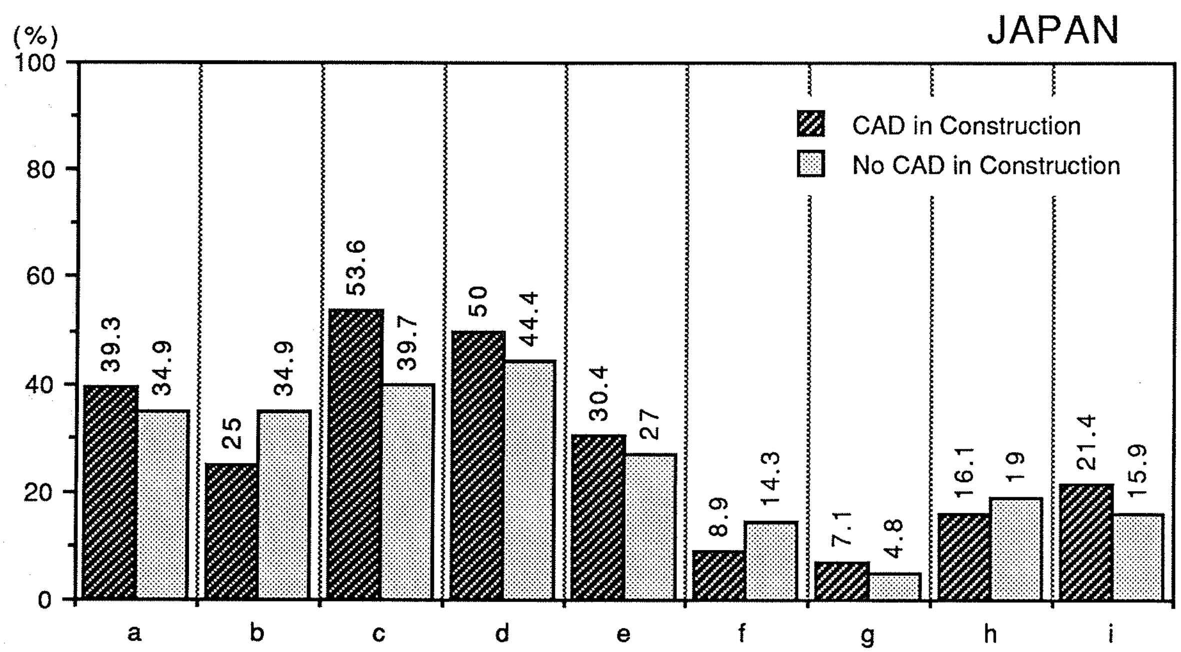


<Construction Operations>
a: coordinate work space
b: prepare concrete lift drawing
c: track as-built drawing
d: monitor and control site layout
e: analyze crane and forklift use
f: planning concrete pumping operations
g: robot control
h: survey control
i: others

<Notes>
- Categories of type of company (Building, Industrial, Civil, Specialty) are not independent
- Specialty on Japanese survey only

Figure 27 Possible CAD Applications in Construction Operations by Type of Company (Question 13)





<Construction Operations>
a: coordinate work space
b: prepare concrete lift drawing
c: track as-built drawing
d: monitor and control site layout
e: analyze crane and forklift use
f: planning concrete pumping operations
g: robot control
h: survey control
i: others

Figure 28 Possible CAD Applications in Construction Operations by Comparison between Companies That Use CAD & Companies That Don't Use CAD (Question 13)

Findings from Tables 4-5 and Figures 29-32

Section II: Barriers

Notes: Questions based on findings of review of "Barriers to CAD in the AEC Industry." Questions have been regrouped for analysis by type of barrier, either organizational (1,3,4,5,6,7,10,11) or institutional (2,8,9). Question 6 was omitted from the US survey because it was improperly edited and senseless.

We calculated weighted averages for each response. We weighed responses as follows: a=+2, b=+1, c=0, d=-1, e=-2. Questions that had a weighted average over 0 were generally considered problems while questions with weighted averages less than 0 were generally not considered problems

- In general, the biggest problems for US and Japanese companies were the lack of trained people, the lack of standards and the cost of CAD systems.

- The Japanese companies indicated that resistance was not a problem at all. This may be because Japanese don't fear losing their jobs when change occurs. The Japanese practice is to train people with new skills when old skills become unuseful.

- Small US companies are more concerned about productivity improvement and cost than medium or large companies.

- Large US companies don't think that cost is a major problem

- Resistance to change is a bigger problem in large US companies than small US companies.

- Few Japanese companies worried about productivity increase or resistance by their employees.

- Large Japanese companies don't think that a lack of understanding of CAD by executives is a problem.

- Many differences between US companies that use CAD and those that don't use CAD.

- US companies that use CAD don't think that productivity is a big issue while those that don't use CAD think that it is.

- US companies that use CAD are less concerned about cost than those who don't use CAD because they understand the benefits better.

- The lack of standards is a problem for all US firms but companies that use CAD think it is less of a problem than those that don't use CAD. Companies that use CAD have developed the standards they need to successfully use it

- Companies that don't use CAD agree more with those who do in Japan than in the US.

- Respondents from both countries highlighted barriers to the use of CAD in construction as shown in Figure 32. These barriers have been categorized as system related, industry related, and facility related.

Table 4 Calculations about Barriers (USA)

		All Companies	Size of Company			CAD in Construction	
			Small	Medium	Large	Yes	NO
Problem 2	m	0.61	0.61	0.54	0.63	0.20	0.84
	σ	1.03	0.93	1.24	0.93	1.12	0.89
Problem 8	m	0.23	0.45	0.00	0.38	0.44	0.11
	σ	1.20	1.25	1.16	1.05	1.17	1.20
Problem 9	m	0.15	0.20	-0.06	-0.06	0.02	0.22
	σ	1.06	1.08	1.13	0.90	1.04	1.06
Problem 1	m	-0.03	0.20	-0.12	-0.38	-0.45	0.23
	σ	1.06	0.83	1.10	1.22	1.13	0.92
Problem 3	m	0.44	0.59	0.30	-0.20	0.04	0.68
	σ	1.14	1.01	1.17	0.83	1.16	1.04
Problem 4	m	0.76	0.71	0.83	0.63	0.61	0.85
	σ	0.98	1.05	0.97	0.48	1.03	0.94
Problem 5	m	-0.25	-0.26	-0.33	-0.25	-0.31	-0.20
	σ	0.99	1.00	1.08	0.75	1.03	0.97
Problem 7	m	-0.21	-0.24	-0.37	0.38	-0.26	-0.17
	σ	1.05	1.04	1.10	0.78	1.09	1.03
Problem 10	m	0.38	0.43	0.48	0.20	0.55	0.27
	σ	1.10	1.04	1.02	1.05	1.06	1.12
Problem 6	m						
	σ						
Problem 11	m						
	σ						

<Notes> m: mean
σ: standard deviation

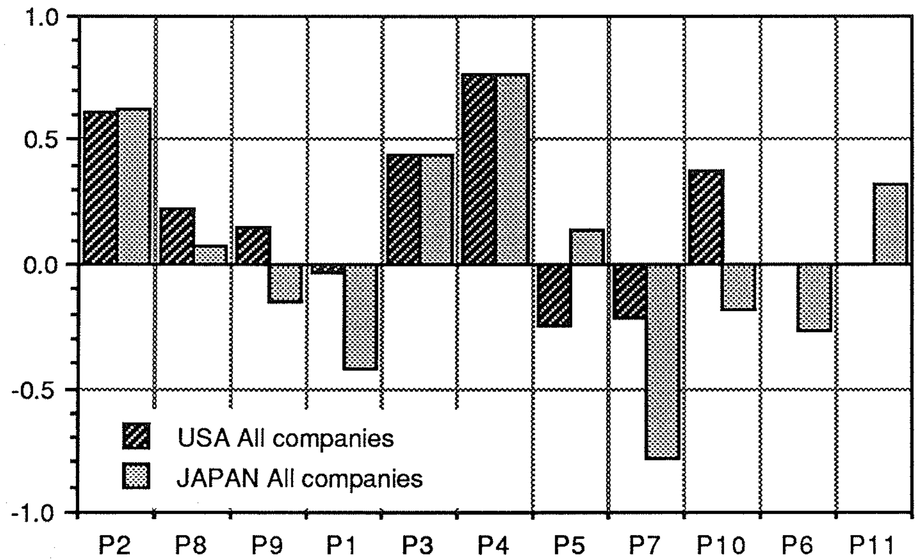
Problem 2: Lack of standards
Problem 8: A/E not required to provide electronic data
Problem 9: Legal and technical problems in transferring design data
Problem 1: Little productivity improvement
Problem 3: High cost
Problem 4: Lack of trained people
Problem 5: Complicated and difficult to learn
Problem 7: Resistance to change
Problem10: Hard to convince project managers costs are upfront, benefits downstream
problem 6: Executives don't understand CAD (on Japanese survey only)
Problem11: Lack of champion (on Japanese survey only)

Table 5 Calculations about Barriers (JAPAN)

		All Companies	Size of Company			CAD in Construction	
			Small	Medium	Large	Yes	No
Problem 2	m	0.62	0.71	0.59	0.48	0.75	0.54
	σ	1.10	1.01	1.11	1.21	1.10	1.06
Problem 8	m	0.08	0.24	0.04	-0.14	-0.06	0.21
	σ	1.24	1.21	1.30	1.12	1.30	1.16
Problem 9	m	-0.15	0.06	-0.29	-0.18	-0.19	-0.08
	σ	1.17	1.01	1.28	1.11	1.21	1.11
Problem 1	m	-0.42	-0.48	-0.43	-0.25	-0.52	-0.31
	σ	1.00	1.02	0.99	0.94	0.93	1.03
Problem 3	m	0.44	0.69	0.25	0.33	0.46	0.45
	σ	1.03	1.10	0.98	0.90	0.97	1.08
Problem 4	m	0.76	0.88	0.71	0.58	0.68	0.82
	σ	0.95	0.82	0.99	1.04	0.99	0.89
Problem 5	m	0.14	0.12	0.16	0.13	0.13	0.15
	σ	1.06	1.11	1.06	0.93	1.10	1.00
Problem 7	m	-0.79	-0.73	-0.82	-0.82	-0.81	-0.71
	σ	1.10	1.10	1.11	1.03	1.05	1.12
Problem 10	m	-0.18	-0.18	-0.21	-0.10	-0.04	-0.27
	σ	1.10	1.08	1.16	0.97	1.08	1.09
Problem 6	m	-0.27	-0.14	-0.22	-0.65	-0.41	-0.11
	σ	1.16	1.07	1.29	0.96	1.16	1.13
Problem 11	m	0.32	0.43	0.25	0.22	0.16	0.46
	σ	1.09	1.01	1.18	1.02	1.10	1.04

<Notes> m: mean
σ: standard deviation

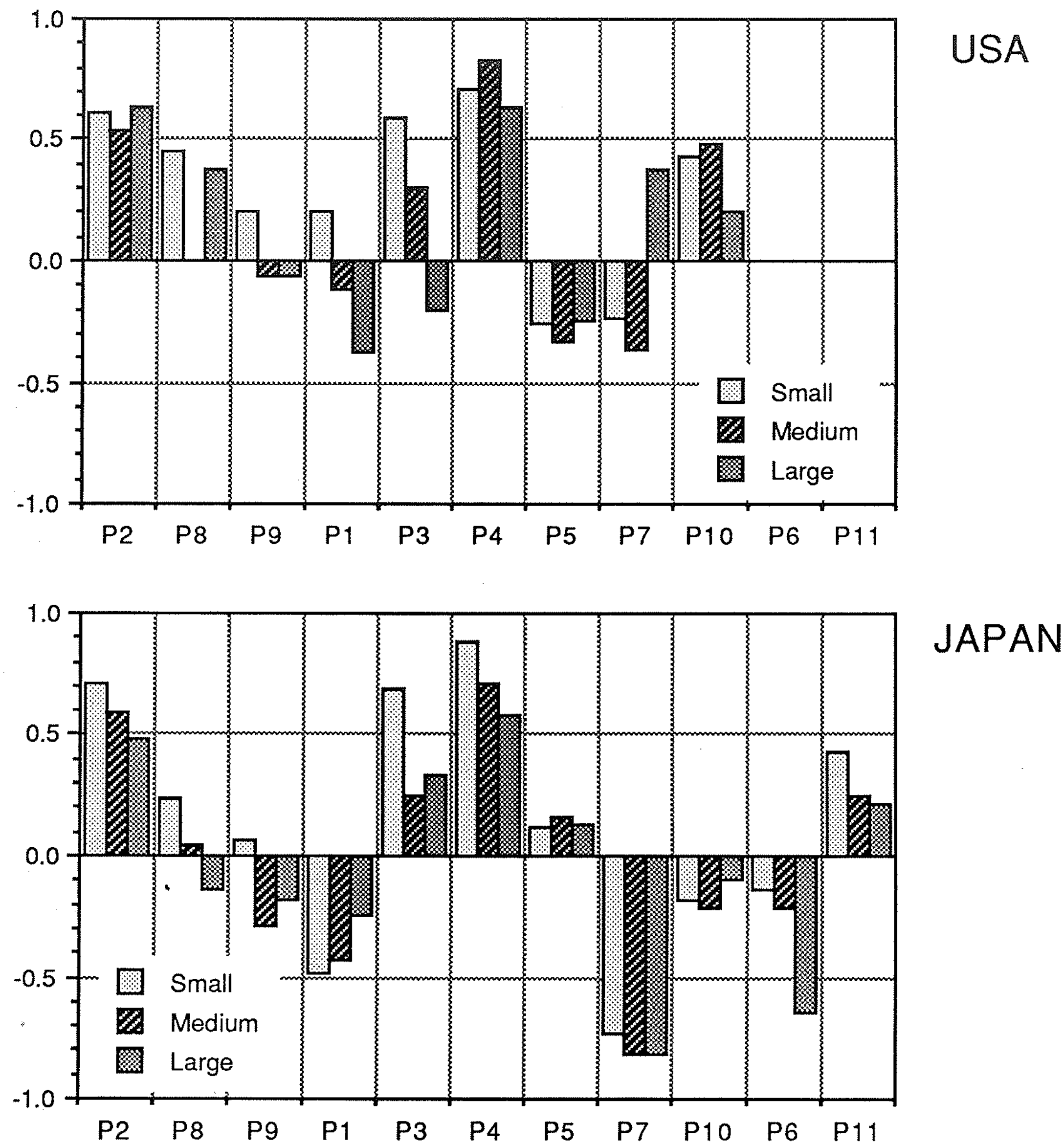
Problem 2: Lack of standards
Problem 8: A/E not required to provide electronic data
Problem 9: Legal and technical problems in transferring design data
Problem 1: Little productivity improvement
Problem 3: High cost
Problem 4: Lack of trained people
Problem 5: Complicated and difficult to learn
Problem 7: Resistance to change
Problem10: Hard to convince project managers costs are upfront, benefits downstream
problem 6: Executives don't understand CAD (on Japanese survey only)
Problem11: Lack of champion (on Japanese survey only)



<PROBLEMS>
P2: Lack of standards
P8: A/E not required to provide electronic data
P9: Legal and technical problems in transferring design data
P1: Little productivity improvement
P3: High cost
P4: Lack of trained people
P5: Complicated and difficult to learn
P7: Resistance to change
P10: Hard to convince project managers costs are upfront, benefits downstream
P6: Executives don't understand CAD (on Japanese survey only)
P11: Lack of champion (on Japanese survey only)

<Notes>
Above axis is problem in general
Below axis is no problem in general

Figure 29 Problems/Barriers to Using CAD in Construction

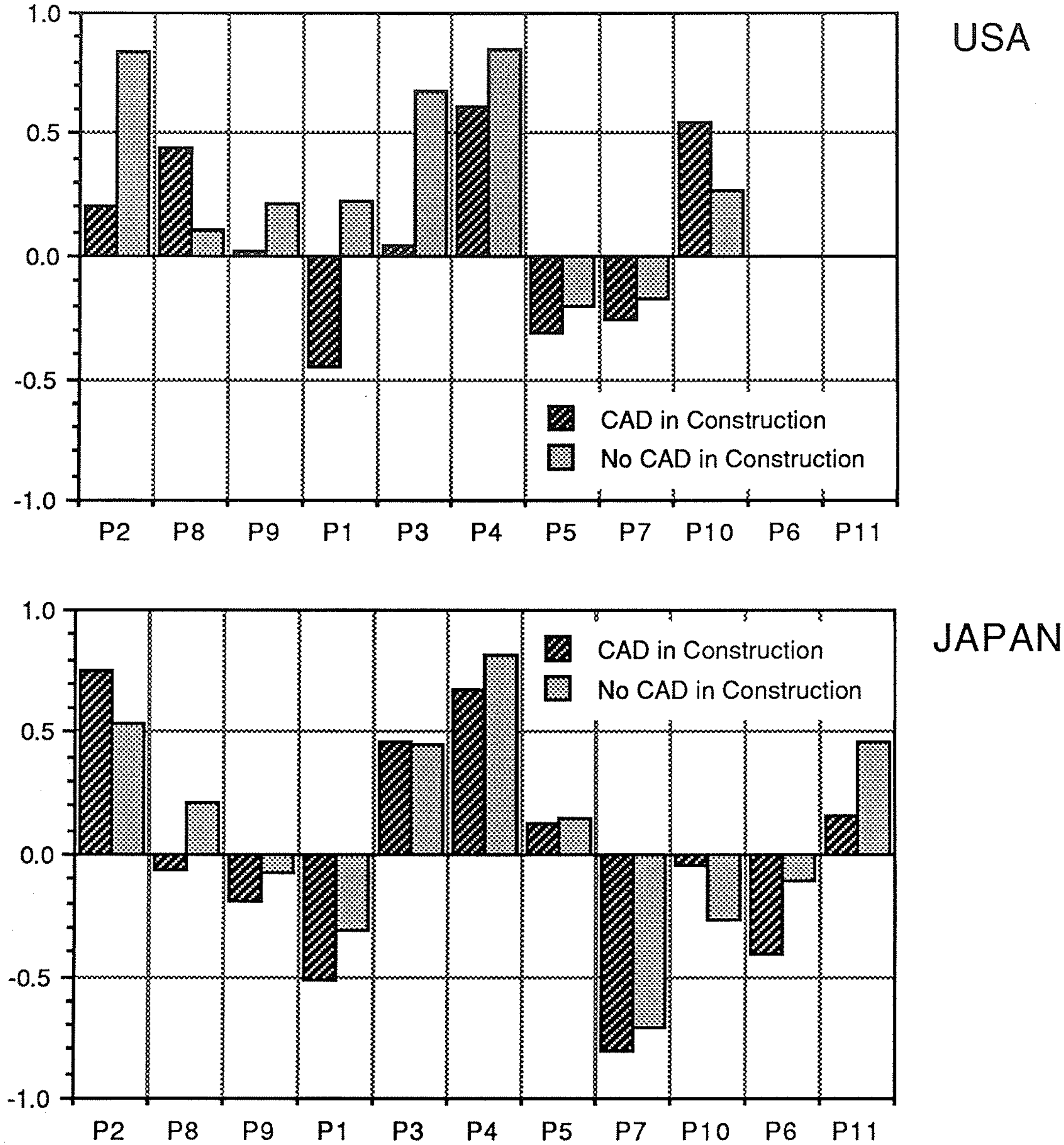


<PROBLEMS>
P2: Lack of standards
P8: A/E not required to provide electronic data
P9: Legal and technical problems in transferring data
P1: Little productivity improvement
P3: High cost
P4: Lack of trained people
P5: Complicated and difficult to learn
P7: Resistance to change
P10: Hard to convince project managers costs are upfront, benefits downstream
P6: Executives don't understand CAD (on Japanese survey only)
P11: Lack of champion (on Japanese survey only)

<Notes>
- Axis
  Above axis is problem in general
  Below axis is no problem in general

- Size of company by annual revenue
  Small: $100M - $200M
  Medium: $200M - $1,000M
  Large: $1,000M -

Figure 30 Problems/Barriers to Using CAD in Construction by Size of Company



<PROBLEMS>
P2: Lack of standards
P8: A/E not required to provide electronic data
P9: Legal and technical problems in transferring design data
P1: Little productivity improvement
P3: High cost
P4: Lack of trained people
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P7: Resistance to change
P10: Hard to convince project managers costs are upfront, benefits downstream
P6: Executives don't understand CAD (on Japanese survey only)
P11: Lack of champion (on Japanese survey only)

<Notes>
Above axis is problem in general
Below axis is no problem in general

Figure 31 Problems/Barriers to Using CAD in Construction by Comparison between Companies That Use CAD & Companies That Don't Use CAD

Figure 32 Problems/Barriers to Using CAD in Construction

1. CAD SYSTEM

i) Hardware:
- High cost
- Incompatibility between A/E's
- Incompatibility between A/E and Construction
- Difficulty in choice of CAD system
- Long drawing time by plotter

ii) Software:
- High cost
- Incompatibility of software
- Lack of useful software
  - Too complicated to learn and use
  - Few software packages linking with estimating and scheduling
  - Lack of software aimed at Construction needs
  - Lack of vendors' recognition about needs of construction industry

iii) Operation:
- Complicated to operate systems
- Not easy for maintenance of system

iv) Database:
- Difficulty in data transfer
  - Use of different hardware
  - Incompatibility of data files
  - Lack of standard of data format
- Lack of substantiality of database

2. AEC INDUSTRY

i) Industry wides:
- Resistance to change
  - Fear of change of working system
  - Traditional industry
  - Implementation of only proven technologies
- Lack of discussion concerning the use of CAD
  - Lack of recognition of benefits of CAD
  - Lack of confidence of introduction of CAD
  - Ignorance of Automation
- Difference environment between Design and Construction for CAD operator
- Fragmentation of construction industry
  - Many different levels of contractor and subcontractors
  - No single contractor in many commercial building
  - Different types of companies work on one project
- Legal problem in data transfer
  - Design ownership
  - Data integrity

ii) Owners:
Owners not involved in Integration
- No requirement of CAD use to A/E's
- No requirement of CAD use to contractors
- No payment for cost of CAD

iii) A/E's:
Many designers don't use CAD or don't complete drawings with CAD

iv) Contractors:
Lack of champions
Inability of construction people to exploit CAD
- Project manager/Field engineer don't understand the benefits of CAD

Lack of trained people
- Small number of CAD operator in construction
- Engineers don't like to become CAD operators
- High turnover of CAD trained people
- Long time to learn CAD

Training issues
- Lack of time to experiment and learn system

Philosophy concerning construction overhead
- Introduction of CAD increases construction overhead

Lack of corporate plans
- Lack of strategies to exploit CAD
- Lack of implementation plans
- Lack of understandings of CAD benefits
- Lack of support system between office and site

System administration
- Lack of system administrators

Environment of field office
- Dust air, temperature, vibration
- Lack of consideration on security/control problems

3. FEATURE OF FACILITY

Lack of standardization of structures
- Unique designs on each occasion (especially in civil works)
- Many unknown factors

Many types/levels of drawing

Variety of components of structure
- Obscurity of logic for small component parts of structure
- Less adjustment between manual work and CAD

BIBLIOGRAPHY

[Bauer 1989] Bauer, Claude J. "PC-Based Software for Contractors." The Construction Specifier, v 42 n 6, June, 1989, pp. 109-119.

This article discusses the increasing use of all sorts of software by construction contractors. Most have focused on using cost control or accounting packages followed by estimating packages. Only a few have attempted integrating CAD with their estimating although the technology exists. Construction companies need to match their needs, the software capabilites and their systems capabilities. The author thinks that serious contractors need to consider 386-based computers. The author also discusses an increasing trend toward integration of different software packages. Total integration is several years away because operating systems, network technologies and hardware need to be fully explored. While the author discusses integrating CAD with estimating and scheduling packages, he does not mention any additional specific applications the contractor may have for CAD.

[Bowerman and Fertig 1988] Bowerman, Robert G. and Fertig, Robert T. "Engineering Workstations: Technology and Application Trends." Van Nostrand Reinhold Company, New York. 1988.

This book discusses hardware and software issues in CAD. It begins by discussing the technological revolution that has occured and assesses the impact of this revolution on engineering workstations. It analyzes different markets and applications. It compares different products in different markets in some technical detail.

[Breen and Kontny] Breen, Willian C. and Kontny, Vincent L. "Automation's Impact on Engineering Design Progress." Journal of Management in Engineering, vol 3, no 4, Ocotober, 1987, pp. 275-280.

This article discusses Fluor Daniel's use of 3D plant modeling systems in their design operations. The authors identify several important benefits of using a 3D modeling system including accurate materials use and quantification, improved drawing production, interference detection, integrating with engineering programs and project management programs and cost savings both in design and construction phases. Construction phase savings stem from reduced rework caused by design problems, accurate and timely material management and reduced construction schedules. To take advantage of these benefits, the authors argue that business will have to plan better to consider smaller more flexible office configurations, higher workforce requirements, shorter design periods, shiftwork, training, and accounting in a more capital intensive environment. The authors insist that 3D modeling for design is here and companies who want to benefit from it must plan their future.

[Burdick 1988] Burdick, David B. "Personal Computers and Workstations Collide." Computers in Mechanical Engineering, January/February, 1988, pp. 12-16.

This article discusses convergence of high end personal computers and low end workstations. While much of the data the authors discuss is outdated, the arguments are more true today than they were in 1988.

[CAD Report 1990] "CAD/CAM, CAE USERS 1990: Current Applications and Future Directions." Computer Aided Design Report, CAD/CAM Publishing, Inc. San Diego,CA 92109-1193.

This report discusses the results from a survey on the current use of CAD. The survey included random samples of firms from the manufacturing, heavy construction, utilities and government industries. 33% of the respondents included engineering services as one of their responsibilities. The survey considered many different areas of CAD use from mechanical engineering, architectural design, numerical control, finite element analysis and electronic engineering applications. In general, drafting is still the most needed applications although more firms are beginning to use CAD for design. Focusing on the architectural uses, the survey concludes that Intergraph, AutoCAD and IBM provide 75% of the CAD systems. The survey does not specifically breakdown applications with the architecural design market.

[Cleveland 1987] Cleveland, Alton B Jr. "CAD, 3-D Modeling and Construction Management." Construction Specifier, v 40 n 4, April 1987, pp 78-83.

In this article, Mr. Cleveland describes some potential applications that he sees for using 3D models to support construction. He argues that before any advances will be made in using 3D models to support construction management, a fundamental shift of orientation away from paper drawings and to the 3D electronic model must be made. Once this shift is made, project participants will be free to use the vast amounts of data available for any purposes that they can conceive and to produce output that specifically supports their intended use. Mr. Cleveland believes that 3D models will produce shorter schedules, fewer job hours and increase quality on any project. Further, construction managers will be able to simulate and plan operations better and use their plans to train the construction crews. He also mentions the construction phase benefits of 3D modeling used in the earlier design phase.

[Cleveland 1989a] Cleveland, A.B. Jr. "Integrating Engineering and Construction Through Automation Technology." In First International Conference on Fossil Plant Construction, edited by C.B. Tatum. Palo Alto, CA: Electric Power Research Institute, 1989.

In this article, Mr. Cleveland describes Bechtel's three basic design automation tools, 3DM, Walkthru and Construction CAE. He discusses these tools in the context of overall project integration. He says that Bechtel designed 3DM to be the central source of design geometry, to perform interactively, to be modular and to employ off-the-shelf products as applicable. Although they designed Walkthru to expand on their 3DM for design, they immediately recognized construction benefits of that technology. He believes that new technologies such as their three systems can change the traditional engineering/construction interface. Such systems can make the design process support the construction process better. He discusses strategies and barriers to integrating the processes. He also believes that new technologies make job site use of their systems possible and desireable although he does not discuss specific job-site applications.

[Cleveland 1989b] Cleveland, Alton B. Jr. "PC's Come of Age for Complex Engineering and Construction Projects." Construction Specifier, v 42 n 6, 1989, pp 76-82.

This article discusses both the evolution of Becthel's 3DM CAD system from mainframe computers to networked PC workstations and the general benefits of integrating the design and construction processes. By the mid-1980's 3D CAD workstations had fallen in price to approximately $80,000-$100,000 per seat. Recent advances in software, hardware and networking technologies have allowed Becthel to move 3DM to networked advanced PC workstations. This new configuration costs approximately $20,000-$25,000 per workstation, offers improved performance, integration, compatiblity and flexibility. Bechtel now uses 386 based computers with math co-processors, additional RAM, large hard disk storage, high resolution monitors, digitizers, communications and CAD software. (Such configurations represent enhancements to systems now commonly found on construction sites but not entirely new systems) This new, cheaper configuration now allows workstations on project sites and should, the author argues, change the process of transfering design information to construction forces. The ability of cheaper workstations to perform advanced 3D modeling will increase integration and impact the entire construction project.

[Cleveland 1989c] Cleveland, A. B. Jr. "Real-Time Animation of Construction Activities." In Proceedings of Construction Congress I--Excellence in the Constructed Project, San Francisco, CA: 1989, pp. 238-243.

This article discusses Bechtel's use of Walkthru to support construction operations. Mr. Cleveland maintains that 3D modeling "makes a tremendous amount of geometric data available to support construction." He discusses using Walkthru to visualize work area, verify proposed construction sequences, traing construction people. He also thinks that the 3D model will drive automated processes but acknolwedges that this area is still in its infancy. The model can be used to insure that selected equipment can properly accomplish a job. It can also be used to acquaint equipment operators with the required manipulations of their equipment to accomplish the job. Mr. Cleveland concludes that the cost of creating and maintaining 3D computer models is less than other modeling alternatives and provides much more flexibility in its use. It improve construction planning, allows them to be complete quicker which in turn allows analysis of more alternatives.

[Gantz 1989] Gantz, John. "Sizing Up the AEC Market." Computer Graphics World, May, 1989, pp. 43-45.

This analysis of the potential of CAD in the AEC market categorizes the market as untapped. Several trends are combining to open the AEC market. The author also notes that so far the AEC market has been particularly prone to using CAD for applications not considered at the time of purchase. He predicts that soon CAD will become a necessity, that depth of use will increase, and that integration issues will become more important.

[Gates and Wickard 1989] Gates, Kermit H., III; and Wickard, Daniel. "Construction-CAE: Integrated Planning and Cost Control." In the 33rd Annual Meeting of the American Association of Cost Engineers, San Diego, CA: 1989.

This article describes Bechtel's Construction CAE project management application. This application builds upon a CAD generated 3D model and integrates various project management functions. The system allows an engineer to assemble the facility from the components designed and represented in a laydown area. The sequence the engineer designates is copied into a scheduling package which generates a project schedule. Other modules consider work breakdown, cost control, management reports and commodity databases. The package attempts to integrate four basic project management functions: objective setting, project planning, project scheduling and analysis. The system is also designed to use a variety of hardware and operating systems Ultimately, the system will include both conventional project planning techniquies and AI/Expert System techniques.

[Gatlin 1989] Gatlin, C.E. Jr. "Benefits of 3D CAD In The Construction of Power Plants" In First International Conference on Fossil Plant Construction, edited by C.B. Tatum. Palo Alto, CA: Electric Power Research Institute, 1989.

This article discusses Fluor Daniel's application of CALMA PDS to their cogeneration construction projects. Mr. Gatlin maintains that PDS allows them to reduce home office engineering and design manhours, shorten project schedules, automate materials take-offs and increase project flexibility. He also elaborates on how PDS contributes to each of these areas. Although Fluor Daniel uses several other systems including AutoCAD and Intergraph, PDS is their primary tool. Working with PDS, they also use Project Review Terminal, a software package that allows them to review their electronic PDS models dynamically. Then entire discussion focuses on the use of PDS as a design tool and subsequent benefits during the construction phase but it does not consider field engineering applications of PDS.

[Gorski et al 1989] Gorski, Catherine M.; Incze, Zoltan ; Rahman, Gregory P.; and Michael J. Williams. "Project Automation Tools on the Basic American I Cogeneration Project." In First International Conference on Fossil Plant Construction, edited by C.B. Tatum. Palo Alto, CA: Electric Power Research Institute, 1989.

This paper discusses Bechtel's attempt to use a variety of project automation tools to support their construction of a cogeneration plant. They used their 3DM system to design the plant initially. This system helped them develop "smart P&ID's," check interferences, prepare accurate piping isometrics, review plant arrangements and sequence activities for scheduling purposes. Their civil group also used the 3DM to produce additional drawings of underground piping, conduit and drainage systems, foundations, piles and above ground steel in critical areas. They also integrated their 3DM model with other project management applications including SYNERGY and SETROUTE. They are also focusing on improving several aspects of their system to provide improved P&ID's and isometrics, integrate analysis applicaitons and to place a terminal in the field so construction forces can view the design model.

[Hollrah and O'Brien 1989] Hollrah, Ronald L; and O'Brien,Darci J. . "Integrated System Innovates Methods of Plant Design and Construction Management." In

First International Conference on Fossil Plant Construction, edited by C.B. Tatum. Palo Alto, CA: Electric Power Research Institute, 1989.

This article discusses Black & Veatch's POWERTRAK system, an integrated system that combines project controls, engineering design and drawing creation. POWERTRAK uses a centralized database to support eight application modules: project scheduling, project cost analysis, manpower reporting, procurement control, drawing control, engineering design, CAE and construction control. POWERTRAK's approach seems somewhat different from other similar packages (i.e. Bechtel's and Stone & Webster's) because the CAD part is only a window on the data rather than the main repository of design information. While the CAD remains the primary input interface of the engineering design, the application modules access the design database, not a CAD database, a subtle but important difference. Black and Veatch is an A/E firm only and does no construction. The article discusses the potential to transfer data directly to other project participants but it does not indicate whether or not this has been done. The article does not discuss any use of this system for field engineering applications.

[Harris-Stewart 1988] Harris-Stewart, Charmaine. "Firms Seek New Measures to Quantify CADD Impact." ENR, November, 1988, pp. 19-20.

This article reports the frustration that several firms have had trying to quantify the bentifits that they receive from their CADD systems. Since firms do not design buildings twice they cannot compare projects. While CAD keeps track of design time, completed similar projects have no records of design times so again comparison is not possible. M.W. Kellogg believes that they enjoy considerable design productivity increases but more importantly the field savings justify their investments in CADD. Another company simply stopped trying to quantify the benefits; they use CADD and they are convinced that they should continue.

[Ibbs 1989] Ibbs, C.W.; and Choi, K.C. "Cost-Effectiveness of Computerization in Design and Construction." A Report to The Construction Industry Institute at the University of Texas, Austin. University of California, Berkeley. January, 1989.

This report discusses the findings of an in depth study for the CII concerning motivations and justifications for using computers, primarily CAD systems, in the construcion industry. The authors focus also on the participation of design firms in the construction industry and all of the contractor companies studied are actually integrated EPC companies who do both design and construct activities. They conclude that the major savings associated with computerization (in the construction industry) come in the form of "downstream" benefits. These benefits improve the construction and facilities management processes and save money for the project overall but they represent savings in one phase that increase costs in other phases. They also conclude that only integrated companies can offset costs with such downstream savings and that currently, contractor only companies are focues on other computerization stategies besides CAD to improve their profit margins.

[ENR 1990] "Integration Aids Productivity." ENR, 6 July, 1989, pp. 22-23.

This article describes work that Summit Constructors, a Denver, Colorado based general contractor has done using CAD. Summit claims that CAD significantly improves their field productivity. CAD aids their detailed design drawing process and also improves their materials management on site.

[Ivany and Cleveland 1988] Ivany, J. and Cleveland, A.B.Jr. "3-D Modeling, Real-Time Computer Simulation Reduce Downtime." Power Engineering, v 92 n 6, June, 1988, pp.49-51.

This article discusses Bechtel's 3DM and Walkthru programs in general terms and in terms of their application to planning a retrofit operation at a nuclear power plant. They cite the main advantages of using 3DM and Walkthru rather than traditional plastic models on this or similar jobs are: economics, configuration, accuracy, usefulness (interference checking), capabilities, permanency, transferability and mobility (videotape). They used 3DM and Walkthru specifically to plan the rigging, removal and replacement of a steam generator, check for interferences and rigging clearances within the structure and at the exit hatch and plan rigging, removal and replacement of the reactor cooling system elbows. One additional product of their system was an animated videotape of the proposed sequence which they showed regulators, owner personnel, construction forces and others concerned about the operation. They maintain the construction of a 3D model from as-built drawings is relatively simple and the use of that model for planning retrofit operations prevents construction difficulties and reduces associated construction costs.

[Killen 1988] Killen, Timothy S. "Design Tools for Construction." National Academy of Engineering Workshop, Woods Hole, August, 1988.

Mr. Killen discusses Bechtel's early adventures in developing their 3D modeling system. They felt that systems available during the early 1980's were inadequate and would not support their requirements. He describes their development efforts and their early applications. One of the important benefits that they identified on their early projects was the improvement in construction due to reduced rework caused by design problems. He also discusses managerial and organizational challenges that their use of CAD created for their company.

[Meyer 1989] Meyer, Ann. "CAD layering Standards." MicroCAD News, August 1989, pp. 57-63.

This article describes the AIA draft layering standard presented at the 1989 AEC Systems Show. Pressure from the industry prompted the AIA, ASCE, ACEC, IFMA, NAVFAC,the Corps of Engineers and the VA to sponsor an effort by the AIA to develop standard layering guidelines for firms in the AEC. Standard layering conventions will ease the transfer of data between different companies and CAD systems. While they found that no one system would solve all problems and that different systems have different constraints, they attempted to form and optimal and ideal system in hopes vendors would modify their products to support the new quasi standard. The system tries to be mnemonic where possible to avoid constant referencing to documents. Other standards have been developed but none has a large following. Anything the AIA work produces will likely be well received.

[Neeley 1990] Neeley, Dennis. "An Indivisible CAD Marketplace?" CADENCE, February, 1990, pp. 65-67.

This article describes a growing market for CAD. It maintains that the market within the A/E community could exceed 1 million workstations. Further, contractors will start to use CAD as it becomes more integrated with other project management applications. The author also maintains that contractors don't balk at the capital investment CAD requires because they are a capital intensive business already. Increased use in facilities management could generate a need for one million more workstations while use in the public sector, though hard to estimate, is huge. The author argues that training will become less of a problem and that the sooner we start to address some of the educational, professional and legal obstacles, the sooner we will be able to fully employ CAD.

[Nevins and Zabilski 1989] Nevins, Daniel P; and Zabilski, Ronald J.. "An Integrated System For Fossil Power Plant Construction and Retrofit Projects." In First International Conference on Fossil Plant Construction, edited by C.B. Tatum. Palo Alto, CA: Electric Power Research Institute, 1989.

This article discusses Stone & Webster's Integrated Plant Database (IPD) system. This system integrates IBM's CATIA and DB2 mainframe 3D modeling and database applications with proprietary applications modules that SW has created. The resulting system integrates many design and construction functions. COMANDS, Construction Management Display System is the particular construction oriented part of the system. The article discusses how they use the system to plan, schedule, manage materials and report progress on their construction projects. Their system relies heavily on the relation between the 3D model and databases. Only geometric data and componenet ID reside in their model. All other important data exists in associated databases. They cite several examples of how construction personnel have used this system to enhance their operations.

[ENR 1989b] "New Association Seeks 'Heroes' of Integration." ENR, 10 August, 1989, pp.23-24.

This article describes a new organization called the Integrated Construction Association (ICA). The ICA is an industry based group of professionals who see the benefits of integrating the construction process and want to push the construction industry towards increased integration. The ICA will focus their efforts on managing existing technologies to integrate the processes because the founding partners agree that current technologies are sufficient and that organizational and institutional problems are the main obstacles.

[O'Connor and Davis 1988] O'Connor, James T; and Davis, Victoria S. "Constructibility Improvement During Field Operations." Journal of Construction Engineering and Management, v 114 n 4, December, 1988, pp 548-564.

This article focuses on innovations during the construction phase of a project. The authors acknowledge that while the leverage of constructibility input added during construction is not as great as during the design phase, the benefits can be substantial. They maintain that "constructibility is enhanced when innovative construction methods are utilized." They indentify seven areas where innovation can improve constructibility: sequencing tasks, temporary materials or structures, hand tools, construction equipment, preassembly, temporary field facilities, post-bid constructor preferences. They also discuss the process of innovation during construction and they conclude that "adaptations of non-construction technologies should not be overlooked" as sources for new innovations. This article comes very close to discussing applications of CAD to support construction. It is not clear whether the authors do not consider this innovative or if they did not consider it at all.

[Peltz 1989] Peltz, Curtis. "The Movement Toward Computer-Integrated Construction." The Construction Specifier, v 42 n 6, June, 1989, pp. 73-75.

This article discusses computer integrated construction primarily in the of integrating design and construction activities through estimating packages. The author offers a broad view of integration of a building life cycle which involves a "growing pool of information which starts with a building's conceptual design pand and ends with its demolition." AutoCAD and Timberline have collaborated to develop a link between CAD and estimating packages, they goal being not to changes how either the designer or estimator must work. The author argues that their system provides a continuous line of information from detailed design through final schedule. The author also discusses the need for improved operating systems and databases to support more advanced integration activities.

[Perkowski 1988] Perkowski, Joseph C. "Technical Trends in the E&C Business: The Next 10 Years." Journal of Construction Engineering and Management, v 114 n 4, December, 1988, pp. 565-576.

[Port 1989] Port, Stanley. "The Management of CAD for Construction." Van Nostrand Reilhold, New York, 1989.

This book describes the use and management of CAD in the general architecture, engineering and construction process with primary focus on the front end of this process. The author first offers some design philosophy and then offers guidelines for planning and implementing a CAD system. Then, he discusses CAD procedures and managerial considerations. Finally, he speculates on other potential uses of CAD information that the designers generate.

[Potter 1988] Potter, Caren D. "Architecture, Engineering and Construction." Computer Aided Engineering, December 1988, pp. 44-50.

The author argues that the Architecture, Engineering and Construction industry has been slow to adopt CAD relative to mechanical or electronics engineers. She cites cost as a major impediment to increased use in the AEC and discusses applications of CAD for the AEC in light of falling prices for the hardware necessary to run adequate CAD programs. She dicusses architectural design, facilities management, civil engineering, mapping, engineering analysis and visualization applications. While she mentions the benefits constructors gain from better designs, she does not discuss how the constructor could use CAD.

[PSMJ 1990] "PSMJ CADD Application and User Survey." Practice Management Associates, Ltd., Newton, MA, 022158.

This report discusses results from an annual survey of CAD use in design firms. The survey addresses CADD Applications and Usage, CADD Staffing and Compensation, Acquisition and Operating Costs, Billing and Productivity and Higher Productivity Firms. Some key findings include: reporting firms use CADD for only 50% of their projects, all use CADD for drafting but only 76% report using it for design and smaller percentages report more advanced uses. Further, CADD costs are down but companies have trouble getting compensated for their use of CADD. High productivity firms have professionals use the CAD. High productivity firms have more trained operators per workstation, use more professionals, use CADD on more projects and use more of CADD's capabilities than the general CADD using population.

[Radoff 1989] Radoff, David. "CAD in Construction." Computer Aided Engineering, May, 1989, pp. 46-50.

This article discusses the use of CAD in construction and problems construction firms have in using electronic design data. The author quotes a representative of NAHB citing that today 5% of construction companies have CAD and this number will double in each of the next two years. The author discusses the link between design and estimating as the main force to entice constructors into an integrated project using CAD. Also the possibility of integrating drawings with cost accounting software could benefit constructors. Currently, though, constructors have trouble getting and using electronic designs from architects. The author quotes others who believe that electronic transfers will be easier when the client requires it and when the architect and the constructor collaborate more closely.

[Reinshmidt 1989]Reinschmidt, Kenneth F; and Zabiliski, Ronald J. "Applications of Computer Graphics in Construction." In Proceedings of Construction Congress I--Excellence in the Constructed Project, San Francisco, CA, 1989, pp. 137-142.

This article discusses Stone & Webster's approach to using their 3D modeling systems to support construction. Although the authors maintain that the data available from the model could support a variety of construction tasks, this article focuses on their use of the model to generate construction schedules. The authors maintain that the use of 3D modeling systems puts the model in the construction planners hands earlier and allows earlier construction planning and constructibility input. Further, electronic models allow the viewer to designate views that support their needs which improve communication. Stone & Webster's system is based on a central CAD database which users can access from many different locations including construction sites. In using the system to generate schedules, the construction planner starts with the 3D model which others designed. The planner assembles the model and his steps are recorded. Since the model is fully 3D, it can calculate numbers, areas and volumes for all components within an area or item that the planner "places." Associated databases maintain material and productivity data so that the schedule can be completed from the logic provided. Further, the planner can experiment with alternate sequences if the original sequence does not provide a balanced approach to the project.

[Simons et al 1988] Simons, Kent L.;Thornberry, Harold L.; and Wickard, Daniel A.. Simulation System for Construction Planning and Scheduling. Presented at the Joint ASME/IEEE Power Generation Conference, Philadelphia, PA, 1988.

This article details the objectives, capabilities and future directions of Bechtel's Construction CAE package. The authors discuss problems with past project planning and scheduling procedures as the impetus of their development effort. Bechtel sought to integrate their 3D CAD models with powerful RDBMS and elementary Expert Systems using Superworkstations. They hoped to produce a product that would aid construction planners visualize portions of facilities, to assist them in making decisions defining work relationships and in exploring alternate construction sequences. They also sought to reduce data entry requirements and improve communications in project planning. This should allow them to detect and resolve problems early, increase the use of 3D models, their associated graphical and nongraphical information and increase opportunities for project integration. The heart of the system is a construction simulator that allows the construction planner to pre-build a project and record his actions for scheduling analysis or communicating sequences to the field crews. Bechtel has developed a very powerful system but it has not been used extensively so actual benefits are unknown. The developers anticipate a variety of benefits which will improve their construction operations.

[Smith, Dana 1989] Smith, Dana K. "Engineering Microcomputer Graphics: A Total Systems Approach." The Construction Specifier, vol 42, no 6, June, 1989, pp. 87-95.

This article describes efforts by the Navy Facilities Engineering Command to integrate the life cycle of their construction projects. They have adopted a modular approach to developing a system that will begin a project based on past projects, maintain current information on designs and costs and ultimately contribute that information back to the historical database. The system will integrate both graphical and nongraphical design information. Currently several modules including conceptual design, costing and specification modules are in place. NAVFAC sees their development effort as an evolutionary process and they don't know where it will ultimately lead. They are convinced, however, that integrating their construction processes will improve both their construction of new facilities and their management of older facilities.

[Smith, Douglas 1988] Smith, Douglas J. "Computer Aided Design and Engineering Leads the Way." Power Engineering, pp. 12-18.

This article discusses how Fluor Daniel, Southern Company Services (the parent company of four major southern power utilities), M.W. Kellogg, Bechtel and Sargent & Lundy use advanced 3D CAD modeling systems to design power plants. The author summarizes the major benefits that these companies realize and identifies optimizing plant construction as a major benefit of the use of 3D modeling in designing power plants. Fluor Daniel reduces installation costs, speeds engineering functions and improves construction scheduling. They also save money on materials through more accurate materials take offs. SCS improves construction in preparing bills of materials and improves design in several ways. Kellogg also acknowledges that 3D modeling significantly improves construction management. Bechtel uses several advanced systems to support design and construction as does Sargent & Lundy. The author is very general in his description of the systems that each company uses and the benefits that they derive from them. He indicates that all benefit during construction but he does not elaborate on any new applications of CAD in construction.

[Stowe 1989] Stowe, Kenneth H. "The Marriage of Computer Automation and Design-Build: Integrating the "C" in AEC." CADENCE, February, 1989, pp. 45-47.

In this article, the author, a charter member of the newly formed Integrated Construction Association describes potential benefits that integrating the construction process can have. He describes a hypothetical construction problem beset with the problems typical in today's construction environment and discusses how such problems could be avoided in an integrated environment. He maintains that advanced technologies are used in a variety of construciton and engineering tasks and that integrating these technologies to support overall project goals will benefit all players. He further maintains that such integration will increase as automation within the industry increases and the Design/Build contract becomes more common. He focuses on the integration of design but does not hypothesize about the sorts of benefits that the constructor will realize from such integration.

[Tatum 1990] Tatum, C.B. "Using CAE to Improve Construction Planning, Operations and Quality." Center for Integrated Facility Engineering, Working Paper Number 8, Stanford University, February, 1990.

This paper discusses the potential that new and emerging CAE tools offer to improve construction operations. It highlights the benefits of CAE in planning connstruction, managing construction operations and improving quality. CAE would allow the use the opportunity to select and plan special procedures, reserve construction space, analyze designs for constructibility, plan installation sequences, check prior installation statuses and plan work changes. CAE aids the construction management by giving construction personnel earlier access to design information and the intent behind the design, the ability to coordinate construciton and provide construction feedback. CAE could improve quality by assisting in the management of the volumes of cross-referenced data required on some complex, high tech facilities. The paper also suggests requirements of CAE packages to accomplish these functions, recommends procedures for developing supporting databases and highlights other current research in this area. The article concludes that while there is much room for improvement, construction managers may benefit the most from facilities designs prepared using CAE tools.

[Teicholz 1989] Teicholz, Paul. "Integration of Microcomputer Applications: Current and Future Approaches." In Proceedings of Construction Congress I--Excellence in the Constructed Project, San Francisco, CA: 1989, pp. 147-157.

Dr. Teicholz discusses various approaches to integrating construciton activities as well as the potential benefits derived from that integration. He offers a definition of integration from the CII which allows multiple users to access the same data which may reside in different locations. The definition allows a modular approach to integration rather than an all encompassing system requirement. He discusses different hardware configurations from single users to networked environments. Further he suggests applications which can and are being integrated such as accounting and cost control and others which have been slow to be integrated such as scheduling. He identifies benefits of integration in construction including: better materials management, improved constructibility, improved scheduling, construction simulation, reduced rework, improved facility operability, improved facilities management, ability to preform QTO, and the potential to drive field robotics. He also maintains that improvements in databases standards, translators and expert systems are needed to fully integrate the construction process.

[CADENCE 1989] "Using AutoCAD Files for Data Reference." CADENCE, September, 1989, pp. 109-110.

This article describes how AutoCAD drawing files can be used as data reference files from which information important to other software applications can be extracted. Drawing files contain both graphical and nongraphical data which can be used in many ways. By extracting information as this article suggests, AutoCAD can become the center of many integrated applications.

[Zabilski and Hall 1989] Zabilski, Ronald J; and Hall, Herschel E. "Presented in 3-D." Civil Engineering, June, 1989, pp. 48-50.

This article discusses Stone & Webster's Integrated Plant Database. Stone & Webster integrated IBM's mainframe based DB2 database and CATIA 3D modeling system with several programs they wrote in-house. The resulting system is a modular, integrated 3D modeling design environment. Most information concering components of their facilities resides in the database where other applications software can easily access it. Only geometry and an identifier code for a component exists in the CAD. The model and the database are dynamically linked. Stone & Webster has used their system extensively in the design and construction of various facilities. To support construction and construction management, a module of the system, COMANDS, allows construction forces to plan and schedule construction process. The construction planner creates a construction sequence model by assembling components as they plan to in the field. In addition to providing interference checks for the sequence, the system also assigns each task to work groups which suppor their work packaging schemes for project management. COMANDS also allows the project management personnel use the model to track construction progress. The system is also useful for plant operations.