CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Incentives for Integrated Facilities Engineering in the Architectural, Engineering, & Construction Industry

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EXECUTIVE SUMMARY

In the last decade, the average workstation cost of a CAD system has dropped to less than a third of what it was previously. An enormous increase in the performance of personal computers has accompanied this reduction in cost. With greater financial accessibility, an increasing number of firms have incorporated CAD systems into their operations. *Progressive Architecture* reports that half of all architectural and engineering firms now use computers as drafting and/or design tools and that nearly all firms plan on using computers for design and drafting by the early 1990's. Furthermore, many integrated engineering and construction companies are beginning to use CAD/CAE for 3-D (3 dimensional) interference checking, material take-offs, environmental performance calculations, and facilities management.

Trade journals and industry magazines are filled with information about the latest hardware on the market, with reviews of various software packages, and with chronicles of the successes and horrors of firms entering the computer age. The sense among many researchers is that the full impact of CAD, or more properly CAE, has yet to be realized. Due to something called "the natural attitude," we tend to live our lives in a way that takes for granted the objects and activities that surround us; even when we encounter something new, we experience it in terms of categories and qualities with which we are familiar.

This report is divided into six sections: 1) how and why firms acquired CAD/CAE, summarizing the responses given by firms to interview questions; 2) current uses of CAD/CAE, drawing on a literature review, user survey, and interviews; 3) characteristics of firms and markets that foster the use of CAD/CAE, also drawing on a literature review, user survey, and interviews; 4) benefits of CAD/CAE for AEC firms, describing how firms are using advanced computer technologies for strategic advantage; 5) a discussion some "reasons behind the reasons" firms acquire CAD/CAE; 6) recommendations for using CAD/CAE, with a forward view of what companies might do to sustain competitive advantage based on CAD/CAE, and an outline of some areas for further research.

Some of the actual and the potential benefits of CAD/CAE involve operational improvements while others offer new marketing methods, optimize resources and expertise, and/or provide closer links to clients. The companies interviewed have used CAD/CAE to create competitive advantage in various ways.

The potential operational benefits to design, engineering, and construction are so great that they are primary incentives for the development of CAE technologies in the AEC industry. Some operational benefits, both actual and potential, are: improving productivity; honing estimates & cost changes; bettering materials procurement & management; compressing & optimizing schedules; upgrading the quality of design and construction; and enhancing communication & coordination. CAE also has the potential to strategically enhance a firm's competitive advantage by: offering new marketing methods; enabling more aggressive pursuit of contracts; opening new markets; optimizing resources and capturing expertise; and providing closer links to the client.

CAD/CAE has become such an integral part of the AEC industry that companies need to do certain things in order to achieve *sustainable* competitive advantage. An approach favored by A.B. Cleveland at Bechtel first suggests that companies steer clear of project oriented CAD/CAE in favor of a process orientation. Second, evolutionary changes are preferred to revolutionary changes. Third, automation systems should be developed to address fundamental, rather than specific, problems. Fourth, if systems are to be designed for change, they need to have an underlying simplicity. And finally, all of the actors involved in developing automated systems need to recognize the various parts of the creative process—"mulling over" the problem, being open to creative insights, and verifying the usefulness of the solution are phases too often skipped.

The basic thrust of this project is to explore *why* AEC companies are using CAD/CAE. Many benefits of CAD/CAE, both operational and strategic, are identified. All of the benefits discussed would provide fertile ground for further investigation. The report just scratches the surface of the actual processes firms go through in deciding which CAD/CAE systems to acquire, when to upgrade, and whether to expand their capabilities. In essence, this is the *how* component of the strategic incentives issue, and it too deserves further attention.

Clearly, CAD/CAE is with us to stay; and developing a better understanding of the way in which this important element of the AEC industry fits into our lives is of considerable consequence to companies, working professionals, and academics alike.

KEY WORDS

Computer Aided Design

Computer Aided Design & Drafting

Computer Aided Engineering

CAD

CADD

CAE

AEC Industry

Architecture

Engineering

Construction

Benefits

Incentives

Decision Making

Strategic

Strategy

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INTRODUCTION

This research project was initiated formally in September, 1989 and draws upon an on-going investigation of the relationship between the adoption of CAD/CAE and strategic decision making. The purpose of the study has been to explore how firms are using CAD/CAE and to discover what, if any, competitive advantages the use of CAD/CAE in integrated facilities engineering yields.

Since the greatest technological impact on integration and the focus of this paper will be CAE, this technology should be defined at the offset. Integrated facilities engineering involves the use of computer automated design (CAD) and computer automated engineering (CAE) tools to coordinate the design, engineering, and construction process. Computer automated engineering in the design and construction process, as used in this report, involves the integration of 2-D and 3-D CAD models, interactive graphics, and a relational database with links to analysis, design and management packages. The database is the heart of the CAE system, the CAD model and interactive graphics are the user interface, and the analysis, design, and management packages are the tools used to design, engineer, and construct facilities.

The project's research methodology involved an initial background literature review, updated periodically; a survey of firms using CAD/CAE; interviews with specific firms; and analysis of the information gathered. The background literature review drew upon trade periodicals, professional publications, academic journals, and transcriptions of speeches given by members of the AEC industry; and it resulted in a paper titled "Advanced Information Technologies in the Architectural, Engineering, & Construction Industry: A Background Review," Appendix E of this report.

The background literature review, Appendix E, is divided into three major sections. The first explores the development of CAD and CAE, in both the AEC industries and others, like manufacturing. The second looks at what advanced users of CAD and CAE are doing within the AEC industry; the systems developed and used by Stone & Webster, Bechtel, and Black & Veatch are described. The final section investigates just what technological and organizational implications these new computer systems have.

Concurrently with the literature review, a telephone survey was conducted with firms whose names appeared frequently in the articles selected and/or with firms having a reputation in the industry for the innovative use of CAD/CAE. Based on the literature review, telephone survey, and willingness of firms to participate, companies representative of various industry sectors were selected to be interviewed. As much as possible, interviews followed the format of the pre-determined interview guide. The companies interviewed included: 1) three large engineer constructors; 2) two consulting architects and engineers; 3) two industrial owners; and 4) two CAD/CAE software developers.[1]

Data analysis followed the information collection period. Emerging patterns of responses to interview questions received particular attention. Analysis included data gathered in the literature review as well as the results of the interviews; and the four objectives outlined in the research proposal focused this examination. These objectives are:

- Explore strategic incentives for the acquisition and use of advanced computer technologies for integrated facility engineering
- Identify characteristics of markets, firms, and projects that foster competitive advantages based on technical capability for integrated facility engineering
- Describe potential benefits for design and construction firms from the strategic use of advanced computer technologies for integrated facility engineering
- Develop recommendations and strategies for acquiring and using advanced technology for integrated facility engineering

This report is divided into six sections: 1) how and why firms acquired CAD/CAE, summarizing the responses given by firms to interview questions; 2) current uses of CAD/CAE, drawing on the literature review, user survey, and interviews to highlight what company's are doing with the most recent software and hardware advances; 3) characteristics of firms and markets that foster the use of CAD/CAE, also drawing on the literature review, user survey, and interviews; 4) benefits of CAD/CAE for AEC firms, describing how firms are using advanced computer technologies for strategic advantage; 5) a discussion some "reasons behind the reasons" firms acquire CAD/CAE; 6) recommendations and strategies for using CAD/CAE, taking a forward view of what companies might do to achieve and sustain competitive advantage based on CAD/CAE and outlining some areas for further research. Readers familiar with current CAD/CAE practices may want to move directly to the benefits and recommendations sections.

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[1] Appendix A contains a list of the hardware, software, and primary applications used by the companies surveyed by telephone. Appendix B is the Research Summary and Appendix C is the Interview Guide which were sent to each firm prior to the actual interviews. Appendix D contains a list of these firms and the persons interviewed.

Computer Aided Design & Engineering in the AEC Industry

In the last decade, the average workstation cost of a CAD system has dropped to less than a third of what it was previously. (See Figure 1 on the following page.) An enormous increase in the performance of personal computers has accompanied this reduction in cost. With greater financial accessibility, an increasing number of firms have incorporated CAD systems into their operations. In 1989 *Progressive Architecture* reported that half of all architectural and engineering firms were using computers as drafting and/or design tools and that nearly all firms plan on using computers for design and drafting by the early 1990's [Fisher 1989]. Furthermore, many integrated engineering and construction companies are beginning to use CAD/CAE for 3-D (3 dimensional) interference checking, material take-offs, environmental performance calculations, and facilities maintenance/management.

Trade journals and industry magazines are filled with information about the latest hardware on the market, with reviews of various software packages, and with chronicles of the successes and horrors of firms entering the computer age. The sense among many researchers is that the full impact of CAD, or more properly CAE, has yet to be realized. Due to something called "the natural attitude," we tend to live our lives in a way that takes for granted the objects and activities that surround us; even when we encounter something new, we experience it in terms of categories and qualities with which we are familiar. For most companies, the organizational issues surrounding the implementation of CAD outweigh the technical [Zuboff 1988].

Interview Results

People make decisions for a variety of reasons, some stated and others more obscure. Social scientists and market analysts spend considerable effort developing explanations for the decisions made by individuals and organizations. They may even go one step farther and create decision-making models. In this section of the report, we approach the questions of "how" and "why" firms acquired CAD/CAE from the point of view of the companies interviewed. The Discussion section of this report offers other possible, unstated reasons which may have been behind the decision to acquire CAD/CAE.

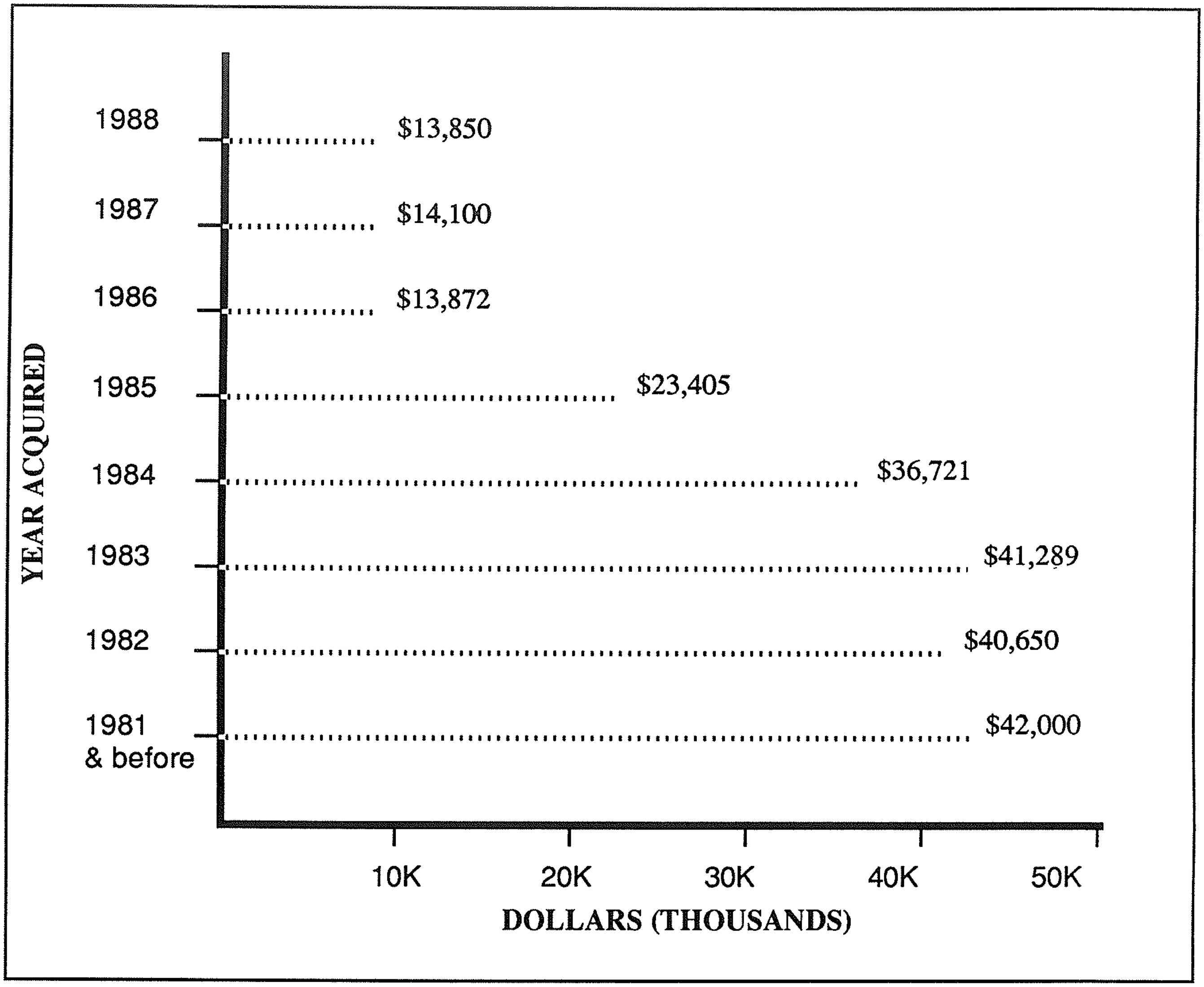

Figure 1 - AVERAGE WORKSTATION COST (Source: Fisher 1989, p.128)

Table 1 lists the reasons the sample companies cited as the primary forces driving the decision to acquire CAD/CAE. The majority of firms interviewed mentioned productivity improvement as the principal reason CAD/CAE was introduced into their organizations. Many companies discovered that the promises made by vendors in the late 1970's and early 1980's turned out to be empty. Early figures of productivity gains, sometimes greater than 10 to 1, helped supporters to win purchase approval; return on investment numbers penciled out nicely. But the projected productivity gains never really materialized. Most firms realized between 3 to 1 and 2 to 1 for the specific task being automated. Nonetheless, probably due to accounting practices as much as anything else, productivity was and remains the most frequently cited reason for acquiring CAD/CAE.

TABLE 1 - DRIVERS for ACQUIRING CAD/CAE*

Productivity Improvement	Design Integration	Stand Alone Capabilities	Capture Expertise	Company Image	Owner Pressure
xxxxxx	xx	xx	x	x	x

* Some companies gave multiple reasons

The second most commonly stated reasons for investing in CAD/CAE are based on the desire to integrated design disciplines and to develop in-house, stand alone capabilities. These reasons generally were given by companies whose full-scale commitment to CAD/CAE came slightly later (in the early 1980's as opposed to the 1970's) than the firms that cited productivity improvement alone. One company interviewed stated that the integration of engineering disciplines was coupled with the urge to concentrate resources in specific geographic areas. Like the aim of improving productivity, at the root of these two stated reasons for acquiring CAD/CAE was the desire to reduce costs.

Many of the firms interviewed mentioned the fact that the work force has changed and will continue to do so. Two firms stated that they adopted CAD when they no longer wanted to depend on service bureaus to supply documents drafted on CAD. One other firm noted that the need to capture the expertise of senior engineers and designers was an important driver in the decision to acquire CAD. The company's hope was that the CAD system, in conjunction with an expert system, could function as a database, collecting important heuristic information developed over a long period of time. Surprisingly, no company mentioned the desire to improve quality explicitly, but the need to integrate functions relates to improved quality.

Two final stated reasons for adopting CAD/CAE have to do with company image and pressure from owners. When at the bottom of its business cycle, a large construction firm began the development of CAD as a kind of desperate measure, believing that the company had to do something–anything!–to set itself apart from others in the same market segment. Surprisingly, only one firm mentioned pressure from owners as a primary decision driver. This result may be a function of the firms selected–because these companies are front runners, they did not wait to make the decision to acquire CAD/CAE until they were forced to.

So much for the "whys" firms gave us for adopting CAD/CAE. What about the "hows"? Table 2 lists the responses given by the companies interviewed. By a large margin, most people interviewed believe that the decision to acquire CAD/CAE was imposed from the top down. Apparently the leaders of these companies had sufficient information, the ability to risk, and/or the vision to think that CAD/CAE had sufficient potential for the organization. In only two cases did the firms note that the impetus for CAD/CAE came from bottom up, meaning that some champion had nursed along the idea for CAD/CAE and eventually sold the concept to upper management. Other means for acquiring CAD/CAE cited by these companies were: 1) incremental growth based on previous computing experience; 2) task force analysis; and 3) vendor involvement.

TABLE 2 - HOW FIRMS ACQUIRE CAD/CAE*

Top Down Decision	Bottom Up Champion	Incremental Growth	Task Force Analysis	Vendor Involvement
xxxxx	xx	x	x	x

* One firm mentioned two influences

CURRENT USES OF CAD/CAE

CAD has been traditionally used in the AEC industry to automate the 2-D drafting process essentially as an "electronic drafting board" [Mahoney 1990]. The introduction of computer automated engineering has accelerated applications of both CAD and CAE technologies. With its fundamental role in integration, CAD use has evolved from 2-D to 3-D design. CAE is typically being used for 3-D modeling and the generation of process and instrumentation diagrams, wiring diagrams, and schematics. Other design applications reported include cut and fill, HVAC, piping, structural, highway, and hydrology.

Leading edge firms have implemented more adventuresome applications based on integrated computer automated engineering systems. Most common is interference checking. Interference checking within the 3-D CAD model has resulted in improved design quality, constructability, and decreased rework. Automated bills of materials and take offs based on the 3-D model linked to the database are becoming increasingly powerful. Specifications, model numbers, procurement status, and vendor data are accessible for all materials as elements of the model. Animation has been integrated with the 3-D model to create "walk through" technologies, especially useful during marketing and project conceptualization. Walk through technologies also are used to plan the construction process. As-built drawings are updated continuously during construction through the CAD model, thereby providing more accurate documentation to the owner.

Integrated CAE systems are being used as interactive facility design and potential construction management tools at several engineering and construction firms. Typical capabilities and applications of these systems can be found in the Computer Automated Engineering Survey, Appendix A.

The most ambitious integration of design and construction to date is in construction simulation [Mahoney 1990]. By linking animation technologies with the 3-D model, the database, and engineering applications, construction operations are being dynamically simulated. The record of the assembly sequence is used to generate detailed schedules which are integrated into global project schedules. Construction equipment and temporary structures models can also be included so the designer can accurately simulate the construction environment. With modeling, animation, simulation, and other ambitious applications in development, integration has set the stage for engineers and constructors to finally reap the revolutionary benefits so long promised from CAD and CAE technologies.

CHARACTERISTICS OF FIRMS FOSTERING CAE

Based on the data gathered from companies participating in the research, firms which foster computer automated engineering share key characteristics. They have a long term vision which targets immediate and downstream benefits of computer automated engineering. They have internal or market drivers for integration of their technologies, processes, or products. They have fully developed traditional CAD technologies and use these technologies as platforms for CAE. They have addressed the strategic development of CAE technologies in their business plans and have assigned managerial authority for this development. Lastly, these firms address the procedural, organizational, and personal barriers to computer automated engineering.

The foremost characteristic is a long term vision which targets the immediate and downstream benefits of CAE. For the design firm, immediate benefits such as design productivity and quality improvements are targeted. Since these firms have no construction capabilities, downstream benefits in construction are unfortunately difficult to harvest. Nonetheless, these firms can target downstream benefits in plant operation, such as future design for process improvement or plant expansion. Plant modifications can be tracked through updating of the 3-D model.

Those best positioned to benefit from the downstream effects of computer automated engineering are the diversified engineering/construction firm and the owner. For the engineering/construction firm, downstream construction benefits such as engineering and construction management integration, materials management, schedule compression, construction simulation, and quality are most readily targeted. The final downstream benefits of CAE are reaped by the owner. Targeted benefits include accurate and easily updated as-builts as well as integrated engineering, maintenance, and process improvement.

Of course, computer automated engineering capabilities would never be developed in any firm without internal or market drivers for integration. For the *design firm,* the primary internal driver is the need to integrate the islands of expertise, technology, or automation from each given engineering discipline. Just as important, the market has come to expect CAD/CAE technologies from leading design and engineering firms and those firms wishing to maintain a leading-edge image can only do so by offering CAD/CAE to their clients.

Integration as a driver is strongest in the *engineering/construction firm* due to its fundamental need to integrate design and construction efforts. For example, engineering changes need to be integrated with construction schedule impacts while field changes need to be integrated into the final design drawings. Market drivers also exist for the engineering/construction firm in that the client often requests CAE capabilities, sometimes even specific systems, in Requests For Proposals.

The strongest market drivers for computer automated engineering exist for the *owner* in that higher quality and cheaper products can be constructed through better design, materials management, compressed schedules, and accurate as-built documentation and databases that can be used for facility management.

Firms successfully tackling the difficulties of CAE have already developed internal CAD capabilities and use these capabilities as a platform to develop CAE. This is true not only because CAE systems essentially are built upon a 3-D CAD and database platform but also because the lessons learned while developing CAD are just as relevant for CAE. Firms which have already addressed issues such as standardization and translation, productivity expectations, and cost justification for their CAD systems have a significant head start in developing their CAE capabilities.

Computer automated engineering requires an extensive development effort involving such diverse elements as system planning, organization of technical personnel, capital expenditures for hardware and software, and training. Firms which foster CAE define the goals of their CAE effort by addressing the strategic development of CAE technology in the firm's business plan and by assigning a managerial authority to oversee the development effort. The business plan may generally address a broad, high-technology thrust or specifically target and assign resources to CAE technologies. Authority for CAE may be assigned to a position with broad managerial responsibilities such as a computer technologies manager or a position more specifically targeted to the technology such as a CAE task force or project leader. While the titles and levels of authority vary, the objective is to designate an authority responsible for developing CAE technology as defined in the firm's business plan.

Firms experienced in the development of CAD have recognized that procedural, organizational, and personal barriers far outweigh the technical when developing CAE capabilities. Firms fostering CAE evaluate, modify, and even purge the tasks which constitute their process of engineering; this is often termed "scrubbing the process." Only tasks inherent to engineering itself need remain for automation. Routine tasks which have lost their meaning may be scrubbed in favor of tasks more efficient or more suitable for the computer automated engineering process.

Firms which foster CAE realize that poor attention to organizational issues may doom an otherwise competent technology. These firms ask the hard questions before pursuing the technology, for example: Where should CAE capabilities be implemented? Should support be centralized or distributed? Will CAE services operate as a profit or cost center?

Since the AEC industry is essentially a service industry reliant on the expertise, competence, and capabilities of its work force, firms which foster CAE pay great attention to its affect on their employees. Beyond extensive training, many jobs may require complete redefinition as CAE is implemented. The line between the drafter, technician, and engineer will almost certainly be redefined. Advocates and adversaries of the technology along with developers, implementors, and users are brought together to form a consensus approach to the technology. Firms which foster computer aided engineering realize that their efforts will only be successful within a work force that is not only capable of using the technology, but confident in the capabilities of the technology itself.

OPERATIONAL AND STRATEGIC BENEFITS OF CAE

The benefits of computer automated engineering are both operational and strategic. Operational benefits are those which directly improve productivity, lower costs, compress the construction schedule, or increase quality during the engineering and construction process. Although operational benefits can certainly be used strategically, we will define strategic benefits as those higher order benefits which enhance the firms competitive advantage in the marketplace.

Operational Benefits

Many computer automated engineering systems are still in trial or development stages. Nonetheless the impacts of their potential operational benefits on design, engineering, and construction are so great that they are primary incentives for the development of CAE technologies in the AEC industry. Some operational benefits, both actual and potential, are:

- Improving productivity
- Honing estimates & cost changes
- Bettering materials procurement & management
- Compressing & optimizing schedules
- Upgrading quality of design & construction
- Enhancing communication & coordination

Productivity. Although CAD has not brought about the order of magnitude increases in design productivity once promised by eager CAD salespersons, CAD and CAE can lower costs through increased design productivity. Increases in design productivity of 25% have been reported for CAD with the greatest results in P&ID's[2], schematics, wiring diagrams, and revisions. If we accept that 75% of the time spent to create a sheet is non-CAD time, and that CAE will impact 50% of that time, we will again see productivity increases when CAE penetrates the design process [CH2MHill].

Another model suggests that logical design (i.e., conceptual design) comprises, say, 20% of design costs while detailed design comprises the remaining 80%. Logical design impacts the majority of the construction costs and CAE will have the most affect on this logical design component [ABB Automation]. Thus, many of the benefits of CAE are downstream of the design process.

Estimates & cost changes. Increases in engineering productivity will be achieved through the 3-D model by automating and integrating the model, bills of materials, take-off, and estimating. Since the 3-D model is directly linked to the database, automated bills of materials are relatively simple and straight forward. The engineer can then utilize this link for take-off. Once take-off and design are integrated, any links between take-off and the estimating package can also be integrated with the model. Within this scenario, changes in the model will be automatically reflected in the take-off and in the estimate. The integration

[2] Piping & Instrumentation Diagrams

of the 3-D model, bills of materials, take-off, and estimate will enable cost impacts of design changes to be automatically generated. Consequently, the design/cost trade-off process will be automated.

Materials procurement & management. In a similar manner, materials procurement and management can be integrated through the automated bill of materials. Thus, changes in the design can automatically be reflected in procurement and inventory status. Better materials management can reduce overages or shortages as well as minimize waste. The result will be lower material overhead costs.

Schedules. CAE's greatest impact may be in schedule optimization and compression. Interference checking within the 3-D model leads to a design that fits together better for improved constructability. Interference checking is already decreasing changes and rework in the field lowering costs and shortening construction schedules. Reported decreases in rework varied; but one company reported a 30% reduction. "Walk through" type technologies allow the owner to better visualize the final product before detailed design and construction, hopefully decreasing scope changes. Construction simulation within the 3-D model will provide automated and optimized scheduling based on simulations of alternative construction methods. Constructability and safety concepts can be integrated into the simulation through expert system packages. Through construction simulation, the schedule impact of changes can also be determined and, when linked with the original estimate as discussed above, will lead to "real time" estimating, pricing, and change order processing.

Quality. CAD and CAE are allowing for the analysis of multiple design alternatives which, if done manually, would be prohibitive due to time and cost constraints. The optimization of these design alternatives will lead to higher quality products for the owner. Documentation of these products also will be improved through more accurate as-builts. The 3-D model can be updated during construction to reflect the final state of the project and used to create a database for facility management.

Communication and Coordination. Lastly, integrated CAE can be thought of as a communication and coordination tool for the engineering and construction process. All the various disciplines, processes, schedules, designs, materials, and people involved can be coordinated around or communicate through one common medium, the 3-D CAD model. The 3-D graphics and database model is a particularly apt medium for communication and coordination as it represents the one common link in the engineering and construction process, the product. Islands of technology and automation will be integrated and coordinated through the 3-D model as will processes and personnel once linked only through a schedule or subcontract. This improved communication and coordination will be instrumental in realizing the operational benefits of CAE in the AEC industry.

Strategic Benefits

Computer automated engineering has the potential to strategically enhance a firm's competitive advantage by:

- Offering new marketing methods
- Enabling more aggressive pursuit of contracts
- Opening new markets
- Optimizing resources and capturing expertise
- Providing closer links to the client

New marketing methods. CAE tools such as 3-D CAD modeling and "walk through" type technologies can be effectively used to market a firm's technical capabilities and visually present a proposed project. Many engineering and construction firms consider the use of CAD and CAE technologies mandatory from their clients' perspective to be considered a leader in the industry. Marketing CAE capabilities through the 3-D modelling medium is a most effective way to demonstrate these capabilities.

The 3-D CAD model has been used to replace the artist's rendering or conventional model when marketing a prospective project. Through the 3-D model, the entire plant can be "built" up-front for the client. Walk Through type technologies provide an even more dynamic marketing tool with potential not only for demonstration to the client but also for governmental and regulatory agencies. Additionally, the 3-D model can provide a basis for the team approach, with owners, AEC professionals, and regulatory agencies working together to accomplish the same objectives.

Aggressive pursuit of contracts. CAE can be used to win contracts. Sophisticated clients are requiring CAE capabilities in their Requests for Proposals. Moreover, firms with CAE capabilities can be more aggressive in the early stages of project development with more accurate estimates and aggressive bids. With the 3-D model, uncertainties in such areas as materials, rework, and scheduling are reduced. Thus the firm's low cost advantage can be enhanced by guaranteeing lower rework percentages, materials overages, or schedule overruns and sharing these savings with the client. Early involve with the owner can lead to away from competitive bids and toward more negotiated work.

New markets. Computer automated engineering can open entirely new markets. New markets entered by engineering and construction firms have included CAE software and systems development and general 3-D computer modelling. With their systems installed in the facility, firms can target markets downstream of engineering and construction such as operations monitoring and control, maintenance, and document control and upstream for planning and environmental permits.

Optimization of resources & expertise. CAE can be used to optimize resources and capture expertise in a declining work force. Integrating former islands of technology and automation will not only reduce rework but will also reduce the duplication of design and engineering efforts. Communication and coordination through the 3-D CAD model will allow firms to geographically decentralize their design staffing as required while still maintaining a centralized design product, the 3-D model. Expert systems and artificial intelligence will be used to capture exiting expertise from the firm and distribute this expertise throughout the incoming work force.

Closer links to the client. Lastly, CAE can be used to establish closer links to the client. Owners are demanding more accurate as-builts to document their facilities and updating of the 3-D model can provide these documents during construction and during operations providing for a long term relationship. Further downstream support in operations management and maintenance can also provide a long term link with the client. The facilities management capabilities of several CAE systems can enable the constructor to better understand the characteristics of the client's facilities and thus the clients long term needs.

Simply having the same system creates an incentive for repeat work. Long term links can also be established by using modeling capabilities for regulatory requirements, feasibility studies for expansion or modernization, and conceptualization of new facilities. In general, enhanced coordination and communication through the 3-D model can benefit the constructor and owner relationship just as it enhances the constructors internal operations. These closer links to the client can be used as a competitive advantage in winning initial contracts and repeat work.

DISCUSSION

Some Other Possible Reasons for Acquiring CAD/CAE

The background literature review indicates that there may be additional reasons for acquiring CAD/CAE, which were unstated by the firms interviewed. Though most of us, engineers in particular, like to think of ourselves as rational creatures, certain semi-invisible forces guide our decision processes. There is wide diversity among researchers as to the relative importance of rational and human behavioral factors in decision making.

When writing about the Cuban missile crisis, one investigator developed three conceptual models of decision making. These are: 1) rational actor; 2) organizational process; and 3) bureaucratic politics [Allison in Quinn et al 1988]. In the first model, action is conceived as a steady-state choice among alternative outcomes. Threats and/or opportunities move the actor to action. The actor has one set of specified goals (the equivalent of a consistent utility function), one perceived set of alternatives, and a single estimate of what might follow from each alternative. In the second model, action is seen less as a deliberate choice of leaders and more as the output of an organization functioning according to standard patterns of behavior. If problems are non-standard, organizations search and learn new routines to assimilate unfamiliar situations. The third model characterizes the decision making process as the result of a series of subtle, intricate, and simultaneous games among players in different parts of the organization; there is unequal power distribution among participants with many separate objectives.

While business strategy literature emphasizes a rational, rules oriented approach, similar to the first model, organizational literature on decision making acknowledges the existence of human behavioral issues. The writing on decision making in organizations is broad and fuzzy. It addresses the possibility of a variety of processes and tends to remain at the theoretical level. However, one theory which must be considered in exploring the decision to acquire CAD/CAE is institutional theory. As W. Richard Scott points out, "institutional features of organizational environments shape both the goals and means of actors" [Scott 1987]. Certainly part of the reason companies, and the professionals within them, are anxious to embrace CAD/CAE has a lot to do with the institutionalization of computer tools.

One of the early influential versions of institutional theory comes from the work of Philip Selznick and his students, Burton Clark, Charles Perrow, and Mayer Zald. Selznick believed that both the characteristics and commitments of participants, as well as influences and constraints from the external environment, shaped organizations. Organizational structure became an adaptive vehicle, and the adaptive process was termed *institutionalization.* To institutionalize is to "infuse with value beyond the technical requirements at hand" [Seznick 1957 qtd. in Scott].

Certainly the firms and professional societies within the AEC industry accept CAD/CAE as part of a belief system that recognizes the importance of computers. Can CAD/CAE instill value beyond instrumental utility? The answer to this question must be "yes" because many AEC firms have just begun to realize a return on CAD investments made over the past ten years. There are many factors involved, such as dramatically reduced hardware and software costs, but firms have stuck with CAD even when the initially promised stellar gains in productivity were not realized. There was some perceived value in CAD beyond its ability to do the job better.

Perhaps this persistence in the use of a computer tool that did not improve the work flow initially can be explained via another conceptualization of institutional theory, which is based on shared social reality. As computers became more common-place in our society, many actors in the AEC industry began to expect their use, i.e., to take their use for granted. These actors included owners, many of whom were high-tech or manufacturing companies who were already using computers with a high level of sophistication. In fact, the largest purchaser of design and construction services in the U.S. is the federal government, which has experience with leading edge technology through the defense industry. Many actors associated with the AEC industry have accepted the notion that using computers is the way things should be done. Could CAD have become a new "rational myth"?

Institutionalization also stresses the role played by symbols, cognitive beliefs, and normative values. Here CAD/CAE are beyond giving reality; they offer legitimacy and increased survival capabilities. At this point, attention is shifted away from the market, customers, competitors and toward the roles of other actors like professional associations. Certainly most of the AEC professional societies[3] have appointed task forces and steering committees to deal with CAD/CAE issues—the development of standards and the legal aspects of stamped drawings[4] are among many hotly debated issues.

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[3] For example: the American Institute of Architects (AIA), the American Society of Civil Engineers (ASCE), the American Society of Mechanical Engineers (ASME), the Institute of Electrical and Electronic Engineers (IEEE), the Construction Specification Institute (CSI), and the Associated General Contractors

[4] Traditionally, drawings have not been considered "legal" unless they bear the stamp and signature of a registered architect or licensed engineer; that drawings residing in computers can be changed or copied easily has far-reaching implications.

In a global sense, most actors within the AEC industry have internalized the "need" for CAD/CAE; but there is diversity of opinion as to how companies should proceed in their efforts to move from CAD into CAE, with customers (owners) and designers/constructors sometimes sharing the same beliefs and oftentimes having differing beliefs. Frequently, owners impose their own preferences for computer systems on architects and engineers. This is somewhat a problem of technology, that is, that information from one system cannot be transferred readily to another. However, it is also an indication that actors within the AEC industry have institutionalized CAD/CAE in varying ways and may be lead to make different decisions regarding upgrading and/or expanding systems.

CONCLUSIONS & RECOMMENDATIONS

General Observations

The true products of CAE are sophisticated computer models, not 2-D drawings. As computing systems simultaneously become less expensive and more sophisticated, the natural attitude may lead us to under utilize the tools available to us, or worse, to use them in a non-productive way. Making this process more difficult is the fact that computers themselves, integrated or otherwise, are changing organizations and the way we work. Most of us just are beginning to comprehend the consequences of computerization and its profound effects: "As information technology restructures the work situation, it abstracts thought from action. Absorption, immediacy, and organic responsiveness are superseded by distance, coolness, and remoteness" [Zuboff 1988]. Even in routine jobs, computers have forced workers to think more abstractly, requiring a new set of competencies.

Now technology exists that can take us beyond the routine. Computer programmers are attempting to automate less well-defined processes like design and management. How will the use of computers affect these areas? Several researchers have suggested that there are short term (up to six months after the the starting point of using computers), medium term (six months to one & one-half years), and long-term (four to five years) effects [Rasmussen, Eriksen, & Hansen in Rader et al 1988]:

- In the short-term we are typically dealing with technical problems of adaptability of the new system to existing requirements.
- The medium-term is related to health and safety problems (stress, visual problems etc.).
- The long-term consequences are related to the change in the way designers use their imagination and logic abilities.

In short, the use of 3-D CAD models may be more limited by our ability to conceptualize the significance of these models than by cost or computer hardware barriers.

Conclusions

This paper has discussed both the actual and the potential benefits of CAD/CAE. Some of these involve operational improvements while others offer new marketing methods, optimize resources and expertise, and/or provide closer links to clients. However, AEC companies already immersed in CAD/CAE are aware of certain hard realities:

- Most software supplied by vendors still targets process plants
- Often there are poor links to structural and electrical systems
- Many vendors do not provide adequate software support
- There is little transferability from program to program and from system to system
- CAD/CAE has become a necessary and expected tool!

While faced with these limitations, the companies interviewed have used CAD/CAE to create competitive advantage in various ways. The potential operational benefits to design, engineering, and construction are so great that they are primary incentives for the development of CAE technologies in the AEC industry. Some operational benefits, both actual and potential, are: 1) improving productivity; 2) honing estimates & cost changes; 3) bettering materials procurement & management; 4) compressing & optimizing schedules; 5) analyzing alternatives; and 6) enhancing communication & coordination.

Computer automated engineering has the potential to strategically enhance a firm's competitive advantage by: 1) offering new marketing methods; 2) enabling more aggressive pursuit of contracts; 3) opening new markets; 4) optimizing resources and capturing expertise; and 5) providing closer links to the client.

Recommendations

If CAD/CAE has become such an integral part of the AEC industry, what can companies do to manage advanced computer systems in order to achieve *sustainable* competitive advantage? A.B. Cleveland, Jr. of Bechtel Group, Inc. has developed an approach which recognizes several fundamental issues: 1) process vs. project orientation; 2) evolution vs. revolution; 3) fundamental vs. specific development; 4) simplicity vs. complexity; and 5) managing the process [Cleveland 1990].

This approach first suggests that companies steer clear of project oriented CAD/CAE in favor of a process orientation. A large number of short term projects can contribute more to the automation of business activities than one long term project. Automation should be thought of as a process. Second, evolutionary changes are preferred to revolutionary changes. Consequently, automation systems must be designed to change. Third, automation systems should be developed to address fundamental, rather than specific, problems. In a complex, dynamic environment systems designed to solve specific problems become useless very quickly. By concentrating on fundamental issues, developed systems can form the basis of many other systems.

Fourth, if systems are to be designed for change, they need to have an underlying simplicity. A complex software system created to represent a complex environment will not have the flexibility necessary to accommodate inevitable shifts and changes. Simplicity (elegance?) is not easy to achieve. Complex systems that address many related requirements may be useful, but they also are expensive to maintain.

Finally, all of the actors involved in developing automated systems need to recognize the various parts of the creative process. Raising the initial question and gathering relevant facts is only the first phase of the process. "Mulling over" the problem, being open to creative insights, and verifying the usefulness of the solution are phases too often skipped.

As a recap of the important observations and conclusions drawn form this research project, the following list of recommendations is offered. When considering CAD/CAD, firms will be best served when they:

1. Realize that organizational issues are as big as technical—learning and change take time
2. Keep current—know what others are doing, especially clients
3. Disseminate information throughout the company—use gatekeepers, or focal points, to keep employees apprised of new developments and expanded capabilities
4. Understand that the roles of workers are changing—designers and engineers will be modelling and drafters will be doing something else
5. Consider new ways of billing services
6. Develop implementation plans and on-going training programs
7. Look at what will happen next—what will be influenced downstream by automation efforts
8. Evaluate, modify, and even purge processes before automating

9. Develop in-house capabilities to help fill gaps in existing technology
10. Realize we are in the beginning of a period of enormous change

Further Research Needs

The basic thrust of this project has been to explore *why* AEC companies are using CAD/CAE. Though we have identified many benefits of CAD/CAE, both operational and strategic, each one of these deserves further attention. All of the operational benefits discussed would provide fertile ground for further investigation. For example, the ways that companies are improving materials procurement and management through CAD/CAE would be of great interest, as would methods for analyzing alternatives and cost changes. The use of CAD/CAE to optimize schedules deserves a study in itself; and the same can be said about enhancing communication & coordination.

Of the strategic benefits outlined, investigating actual as well as potential means by which companies either have gotten closer or could get closer to clients through the use of CAD/CAE would make a significant contribution. Surveying the manner in which companies are using CAD/CAE in marketing and in opening new markets would improve our understanding of strategy development meaningfully. Also, exploring methods of using CAD/CAE for capturing existing expertise in a world of changing employee demographics would assist firms to optimize their resources.

Furthermore, in this report we have just scratched the surface of the actual processes firms go through in deciding which CAD/CAE systems to acquire, when to upgrade, and whether to expand their capabilities. In essence, this is the *how* component of the strategic incentives issue. How do companies develop their strategic plans? How do players external to the strategy formation process—competitors, design professionals, vendors, internal champions, clients—exert forces on the decision-making process? How do other factors—risk analysis, feasibility studies, timing, company performance, market conditions—influence decisions? And finally, how do existing resources—technical know-how, technical literacy of employees and managers, and computers—affect strategy? These how's of decision making have not been addressed adequately.

Clearly, CAD/CAE is with us to stay; and developing a better understanding of the way in which this important element of the AEC industry fits into our lives is of considerable consequence to companies, working professionals, and academics alike.

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APPENDIX A - COMPUTER INTEGRATED ENGINEERING USER SURVEY
K. Hansen/K. Johnson

Company	Hardware	Software	Capabilities	Primary Applications	Notes
Bechtel Power 1540 Shady Grove Rd Gaithersburg, MD 20877-1454	Workstation: 80386 PC, 2-10 MB memory, hard-disk drive, two high resolution color monitors, mouse or digitizing tablet, ethernet communications Server: VAX computer	3DM, a 3-D plant design system developed in-house, DECNet DOS communications software, Microstation CAD software. "Walkthru" simulation.	Integrated 3-D design and engineering including geometric modeling, drawing/data extraction, interference detection, CAE interfaces, database management and animation.	Plant design, engineering, construction, operation and simulation.	Soon to implement "Construction CAE", an integrated construction engineering/simulation package
Stone & Webster Engineering Corp. P.O. Box 2325 Boston, MA 02107	IBM host (4381) serving IBM 5080 graphics systems or PC/2 micro computers.	IBM : relational database DB2, computer graphics systems CADAM or CATIA, expert system ESE. Integration software developed in-house.	Integrated 3-D design & engineering: geometric modeling, intelligent drawings, plant maintenance, quality control, animation, & database management.	Design, engineering, construction & operation of utility systems and power plants.	
Ebasco Services Inc 2 World Trade Center New York, NY	Ebasco is no longer pursueing integrated CAD systems and is instead purchasing off the shelf PC design/engineering software & hardware. Please see phone interview notes of 10/31. -KJ				
Black & Veatch P.O. Box 8405 Kansas City, MO 64114	DEC-VAX application specific processors & Briton-Lee database processor serving AT&T and Micro Vax workstations, DECNET network	Powrtrack, a computer automated engineering and information system developed in house. Multiple integrated modules as described in capabilities. 3-D graphics by Evans & Sutherland. 2-D graphics by Auto-trol, Intergraph or AutoCAD.	Integrated engineering and information management including 3-D modeling, CAE, engineering design, construction control, project scheduling, drawing control, procurement control, project cost analysis, & manpower reporting.	Design, engineering, construction, operation, management, and maintenance of power utilities.	All data are developed, stored, maintained, and used from the single data base. All applications are integrated around the database.
ABB Automation 960 Atlantic Ave. Alameda, CA 94501	IBM or VAX host serving IBM PC or DEC CPU, DECnet/DOS communications	PASCE, an integrated 3-D plant engineering system developed in house. Modules: Plant VIEW, PlantSCHEMA, PlantWALK, PlantLINK, & PlantDRAFT	Integrated design and engineering including 3-D physical modeling, process simulation, schematic modeling, animated walk-thru, pc/vax integration, database management.	Power & chemical process plant design, engineering, simulation, optimization, and maintenance.	Formally C-E Automatio
Flour Daniel 3333 Michelson Dr. Irvine, CA 92730	VAX based workstations w/Ethernet, Apollo, and Novell networking	Calma - 3D plant design and Intergraph CAD 2D & 3D	Automatic materials take off and bills, interference checking, P&ID's, stand alone project review terminals, 3D modeling	Plant design, engineering, and modeling	
H.A. Simons 425 Carrel St. Vancouver B.C., Canada V6B 2J6	Vax system serving various workstations	Intergraph CAD 2D/3D and PASCE	Plant design and modeling as per PASCE system above	Design and 3D modeling and paper and pulp plants	
CH2M Hill 2399 NW Walnut Corvalis, OR 97339		Intergraph CAD 2D/3D	Plant design and 3D modeling	Environmental plant design and engineering - all disciplines	
PG&E 345 Mission St. San Francisco, CA 94106		Intergraph CAD 2D/3D	Plant design and 3D modeling	Powerplant design. Bill of material take off and generation.	

APPENDIX B
Research Summary
"Strategic Incentives for Integrated Facilities Engineering"

"Strategic Incentives for Integrated Facilities Engineering" is a research effort of the Center for Integrated Facilities Engineering (CIFE) at Stanford University. This project is a portion of the research underway in the Managment of Technology thrust of CIFE. The goal of this research thrust is to increase understanding of the management issues that affect new technology and to help overcome barriers to the development of new technologies for integration. The researchers are Bob Tatum, Karen Hansen, and Kyle Johnson. A portion of Karen's doctoral work is being combined with the research.

Specific objectives of the research include the following:

1. Explore strategic incentives for the acquisition and use of advanced computer technologies for integrated facilities engineering.

2. Identify characteristics of markets, firms, and projects that foster competitive advantages based on technical capability for integrated facility engineering.

3. Describe potential benefits for design and construction firms from the strategic use of advanced computer technologies for integrated facility engineering.

4. Develop recommendations and strategies for acquiring and using advanced technology for integrated facility engineering.

In this context, strategy can be defined as the planning mechanisms, decision making processes, and organizational structures that companies use to achieve specific business goals. The objectives of the research do not include the confidential business plans and strategies of any company.

The research method is as follows:

1. Review background literature describing the uses of technology to gain competitive advantage.

2. Describe potential competitive advantages and strategies based on the acquisition and use of advanced computer technologies for integrated facility engineering.

3. Interview managers from owners, contractors and designers to evaluate the competitive advantages and strategies.

4. Develop findings to highlight the competitive incentives for integrated facility engineering.

Karen Hansen's doctoral research involves the decision making processes surrounding the acquisition of C.A.D.D. (computer aided drafting and design) within architectural, engineering, and construction firms. Her research will address the mechanisms and circumstances surrounding the incorporation of C.A.D.D. technology into the company organization and into long range planning.

The research is expected to yield technical papers describing the potential competitive advantages and strategies that provide incentives for integrated facility engineering and a doctoral thesis from Karen Hansen. These publications will emphasize the many incentives for firms to break the constraints of believing that "we have gone about as far as we can go".

APPENDIX C
INTERVIEW GUIDE
"STRATEGIC INCENTIVES FOR INTEGRATED FACILITIES ENGINEERING"

1. **Background**
   a. What is your company's primary market(s).

   b. Who are your major clients and competitors.

   c. What is the annual sales volume/revenue of your company and how many salaried personnel do you employ?

2. **Decision to acquire or develop CADD/CAE**
   a. When did you start thinking about acquiring or developing CADD/CAE?

   b. What were the important issues and considerations at that time and what benefits were anticipated?

   c. When did begin developing your present system and when was it implemented?

   d. Who in your organization was involved in the decision to develop your system and what influence did they have on design and development?

   e. Who championed & who resisted the development of the system?

   f. Was the technology for your system available before the market for it developed?

3. **Organizational aspects of CADD/CAE**
   a. What organizational divisions within your company utilize the system and where has the system had its greatest success?

   b. Where within your organization has the system had its least success?

   c. How has the system affected the administrative aspects of your organization such as accounting, payroll, or personnel?

d. Who holds primary responsibility for the system within your organization?

4. Impact of CADD/CAE

a. Where does your system fit into your business plan?

b. Have you developed new project capabilities or entered new markets because of your system?

c. Can you win jobs by using CADD/CAE for competitive advantage?

d. How have your CADD/CAE capabilities influenced your marketing strategy?

e. What advantages does your system provide during the construction process and in what areas have costs been lowered due to the system?

f. Do any of your clients formally or informally request computer aided design and engineering capabilities when inviting bids?

g. What mechanisms do you employ to sustain the benefits of your system (e.g. standardization, patents, licensing, etc.)

h. What other incentives do you see for integrated facilities engineering in the AEC industry?

APPENDIX D
Interview Listing
"Strategic Incentives for Integrated Facilities Engineering"

1.) *Bechtel Group Inc.*
Mr. Timothy Killen, Manager of Engineering & Construction Technologies, Research & Development

2.) *ABB Automation* (formally C-E Engineering Automation)
Mr. Rick Carell, Marketing Manager

3.) *Ebasco Services Inc.*
Mr. Alfred Wern, Chief Civil Engineer

4.) *Autodesk, Inc.*
Mr. Cliff Gauntlett, Director AEC Technology

5.) *H.A. Simons Ltd.*
Mr. John Spencer, Director Technology, Strategic & Development
Mr. Edward Kaczmarek, Manager Engineering Services Department

6.) *CH2M Hill*
Mr. Allen L. Davis, Director Computer Aided Engineering

7.) *Boeing Aerospace*
Myril Shultz, Director of Facilities
Dexter Eng, Facilities Systems Manager

8.) *Boeing Commercial Airplanes,*
Endora M. Engbretson, Facilities CAD System Manager

9.) *Flour Daniel*
Kirk D. Grimes, Manager of Engineering Graphics

10.) *Pacific Gas & Electric Company*
Mr. Ken Lewis, Manager Substation Engineering & Construction
Mr. Robert J. Thompson. Project Manager, Substation Engineering and Construction

APPENDIX E

Background Review

ADVANCED INFORMATION TECHNOLOGIES and the ARCHITECTURAL-ENGINEERING-CONSTRUCTION INDUSTRY: A BACKGROUND REVIEW

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January 1990

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KEY WORDS

Computer Aided Design
Computer Aided Engineering
Computer Aided Manufacturing
Computer Integrated Manufacturing
CAD
CADD
CAE
CAD/CAM
CIM
AEC Industry
Architecture
Engineering
Construction

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ABSTRACT

The purpose of this paper is to provide background information for research funded by the Center for Integrated Facilities Engineering (CIFE), within the Department of Civil Engineering at Stanford University. The funded research project involves strategic incentives for integrated facilities engineering, with particular emphasis on the potential benefits to be derived from the adoption/development of computer-aided drafting, design and engineering (CADD and CAE).

Using the philosophy that one must understand the state of practice as a basis for investigating strategic opportunities, this paper summarizes the current literature addressing CADD and CAE. It attempts to shed some light on how the increased development and implementation of computer information technologies may affect architects, engineers, and contractors. In the last decade, the average workstation cost of a CADD (Computer Aided Design & Drafting) system has dropped to less than a third of what it was previously. *Progressive Architecture* reports that half of all architectural and engineering firms now use computers as drafting and/or design tools and that nearly all firms plan on using computers for design and drafting by the early 1990's. Furthermore, many integrated engineering and construction companies are beginning to use CADD for 3-D (3 dimensional) interference checking, material take-offs, environmental performance calculations, and facilities maintenance/management.

Using CADD at the initial level requires only the knowledge of the necessary graphic commands and a minimal amount of office reorganization; the complete impact of CAE (Computer Aided Engineering) on the architectural, engineering, and construction industry will be felt only when practitioners change their perceptions. The true products of CAE are sophisticated computer models, not 2-D drawings. As computing systems simultaneously become less expensive and more sophisticated, we can wonder if a "business-as-usual" attitude may lead us to under utilize the tools available to us, or worse, to use them in a non-productive way.

The paper is divided into three major sections. The first explores the development of CADD and CAE, in both the AEC industries and others, like manufacturing. The second looks at what the most advanced users of CADD and CAE are doing within the AEC industry; the systems developed and used by Stone & Webster, Bechtel, and Black & Veatch are described. The final section investigates just what technological and organizational implications these new computer systems have. A glossary of frequently used terms & abbreviations is provided at the end of the text.

INTRODUCTION

In the last decade, the average workstation cost of a CADD (Computer Aided Design & Drafting) system has dropped to less than a third of what it was previously. (See Figure 1.) With greater financial accessibility, an increasing number of firms have incorporated CADD systems into their operations. *Progressive Architecture* reports that half of all architectural and engineering firms now use computers as drafting and/or design tools and that nearly all firms plan on using computers for design and drafting by the early 1990's [Fisher 1989, p. 126]. Furthermore, many integrated engineering and construction companies are beginning to use CADD for 3-D (3 dimensional) interference checking, material take-offs, environmental performance calculations, and facilities maintenance/management.

Trade journals and industry magazines are filled with information about the latest hardware on the market, with reviews of various software packages, and with chronicles of the successes and horrors of firms entering the computer age. But, as we shall see, the sense among many researchers is that the full impact of CADD, or more properly CAE (Computer Aided Engineering), has yet to be realized. Due to something called "the natural attitude," we tend to live our lives in a way that takes for granted the objects and activities that surround us; even when we encounter something new, we experience it in terms of categories and qualities with which we are familiar [Zuboff 1988, p. 14]. Using CADD at the initial level requires only the knowledge of the necessary graphic commands and a minimal amount of office reorganization; the complete impact of CAE on the architectural, engineering, and construction industry will be felt only when practitioners change their perceptions.

The true products of CAE are sophisticated computer models, not 2-D drawings. As computing systems simultaneously become less expensive and more sophisticated, we can wonder if the natural attitude may lead us to under utilize the tools available to us, or worse, to use them in a non-productive way. Researchers have expended considerable energy examining CIM (Computer Aided Manufacturing), but less attention has been directed toward the AEC industry. The purpose of this paper is to shed some light on how the increased interest in computer information technologies may affect architects, engineers, and contractors by : 1) exploring the development of CADD and CAE, in both the AEC

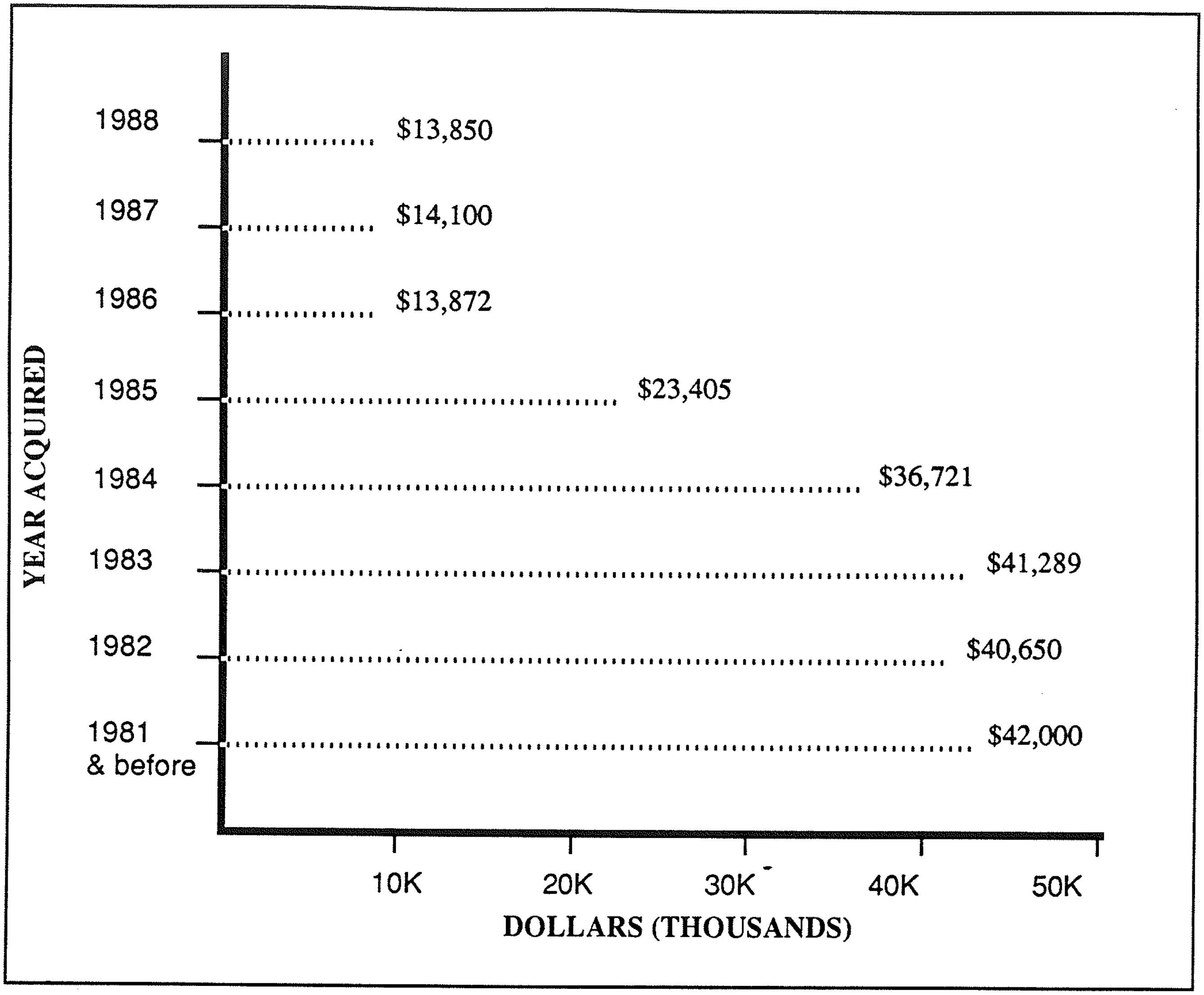

Figure 1 - AVERAGE WORKSTATION COST (Source: Fisher 1989, p.128)

industries and others, like manufacturing; 2) seeing what the most advanced users of CADD and CAE are doing within the AEC industry; and 3) investigating just what technological and organizational implications the new computer systems have.

DEVELOPMENT OF COMPUTER AIDED DESIGN & DRAFTING (CADD) and COMPUTER AIDED ENGINEERING (CAE)

This section of the paper examines several topics related to the development and evolution of CADD and CAE systems. First is a brief description of the way three dimensional computer models are created. Second is a kind of "Reader's Digest" version of some of the important milestones in history of CADD. Next is a look at CADD's commercial development. Finally there is an overview of some of the current approaches to computer integrated manufacturing (CIM).

Background

In a CADD model, primitive objects, or primitives, are the basic building blocks. On two-dimensional drawings, primitives include points, lines, arcs, and text. A primitive in a three dimensional model is defined as: "a set of points, lines or edges, curves, or surfaces that defines a single complete and unambiguous volume" [Schilling 1987, p. 207]. Three dimensional primitives appear as shapes approximated by straight lines, or more accurately, lines connecting points. Curves can be represented by a set of vertices, a set of parameters such as radius and included angle, or as a a pair of points and a pitch or tangent angle associated with each point. In general, three dimensional primitives, whether stored in either boundary representation (Brep) or constructive solid geometry (CSG) form, only can be further reduced to points.

In order to create models of real-life objects, CADD systems use various utilities. Both 2-D and 3-D systems use utilities for drawing lines and arcs, rotating, copying and mirroring objects. Additionally, 3-D systems create objects by: 1) modifying generic primitive objects; 2) extruding or generating swept objects; 3) connecting polygons or surfaces; 4) placing points in three dimensional space; and 5) cutting objects [Schilling 1987, p. 209]. Table 1 on the following page explains these utilities is more detail.

A variety of techniques, usually overlapping, are available to construct three dimensional models from three dimensional primitives. These include extruding two dimensional plans, using markers in two dimensional plans to locate 3-D primitives, and placing 3-D primitives in space with Cartesian coordinates. Another operation, direct model building, scans an existing object and creates a three dimensional model within the computer.

TABLE 1 UTILITIES USED IN 3-D MODELING

UTILITY	OPERATION
Modified generic primitives	Default value dimensions for spheres, cylinders, tubes, cones, blocks, pyramids, & tori (doughnuts) are altered; then these primitives are combined to create more complex shapes.
Extrusions	A section is drawn in 2-D as a combination of lines and arcs; the section is then rotated about an axis sweeping out a shape.
Connected polygons	Sections are created in 2-D & oriented in space by translating, tilting, or rotating; then points along the edge of one section are connected to points along the edge of another section.
Points in 3-D space	A point on the surface of a 2-D section or isometric projection is connected to another point in space; a series of points are connected until the lines between the points form a volume.
Cutting objects	One 3-D object modifies another 3-D object by overlapping or abutting it; one object may cut a volume out of the other.

The "Invention" of CADD

Retracing the development path of computer aided design would be an winding and, as yet, uncompleted journey. Some researchers mark its origins as the early 1950's when the Computer Applications Group of the Electronic Systems Laboratory (formerly the Servomechanisms Laboratory) at MIT pioneered paper tape control of machine tools [Elliott 1989, p.275]. This effort lead to the development of APT, Automated Programming for Tools, a new computer language created at the Illinois Institute of Technology Research Institute and funded by the US Air Force [Elliott 1989, p.275][Bézier 1989, p.259].

During the late 1950's, the US Air Force continued its support of what was to become computer aided design through the work of Dwight Baumann and Steven Anson Coons of MIT Mechanical Engineering and Douglas Ross of MIT Computer Applications Group. These three researchers along with Ivan Sutherland, also of MIT, presented papers at the 1963 Fall and 1964 Spring Joint Computer Conferences. Sutherland's work on Sketchpad, a computer system using graphics display for design, ignited a fire; and funds were sought by other researchers to "apply" Sketchpad [Elliott 1989, p.275].

Meanwhile, still other researchers continued to work on the geometrical problems of computer aided design. In the mid-1960's, Steven Coons invented a method—the Coon's Patch—for defining complex curves. His solution, a patch-enclosing net which ensures slope and/or curvature continuity, "is considered a milestone in CAD development" [Bézier 1989, p.259]. Also during the 1960's, Bézier working at Renault developed an approximation method for generating free-form curves or splines [Piegl 1989, p.266]. Two and three-dimensional drafting, wireframe, and sculptured surface systems followed quickly. During the 1970's, software for 3-D solid modeling and shaded color graphics was developed along with many engineering analysis packages linked to CADD [Majchrzak et al 1987, p.3].

Early CADD applications were expensive, and cost-benefits only could be obtained for complex or high value products, where the possibility of time and cost savings were greatest. Thus, the electronic, chemical, aerospace, and automotive industries were the initial leaders [Llewelyn 1989, p.300]. Robotics and flexible manufacturing created new requirements for image recognition and the consequent need to integrate these images with the established methods of object definition in CADD.

From a purely technical standpoint, much of the basic CADD groundwork has been laid. Current debate among system developers and users centers around the development of standards and the philosophical approach to storing information [Smithers 1989, p.141]. One can theorize about where the next step in computer technology might take us. According to Llewelyn [1989 p.299]:

> ...the advances made, including fifth generation computers, all depend on symbol manipulation and instruction processing. It is, therefore, interesting to speculate on the way neural networks or connectivity machines, with appropriate simulation software, could extend the performance of current systems and deal adequately with accumulated information and experience. The ability to cope with 'fuzzy data' through associative memory, and learn from stored information rather than just catalogue it in a database for search and retrieval, would represent a major advance bringing together design, production, finance and management.

Commercial Development

While these theoretical advances represent the technology push side of the equation, market forces also have influenced the development of CADD. Some vendors got into the market by producing software while others manufactured hardware; but the vendors who captured the largest share of the market initially were those that offered "turnkey" systems, including hardware, software, and service in one comprehensive package, that ran on either mainframe or minicomputers [Goetsch 1988, p. 5]. Table 2 on the following page profiles these vendors.

Although microcomputer based CADD systems existed in the late 1970's, they lacked serious design an drafting capabilities. Several of these "toy" systems were used in the education market, where training and not productivity was the objective. Most of the problems with early microcomputer CADD systems–inadequate processing power and graphics capacity–stemmed from limitations of the microcomputer. By the early 1980's, increased memory, faster processing speeds, and enhanced graphics capabilities became a reality. High-resolution color monitors and hard disk drives were available at affordable prices. Turnkey micro CADD systems ranged in price from $4000 to over $20,000, typical systems initially costing between $8,000 and $10,000 [Goetsch 1988, p. 13].

Approximately 40% of the microcomputer based CADD systems installed currently are based on IBM equipment. At present there are over 200 vendors, but as with the mini and mainframe based systems, a handful of vendors holds the lion's share of the market. The leading vendors are: AutoDesk, Cadcal, Cubicomp, Terak, Engineering Automation Systems, Summit CAD, Cascade, T&W Systems, Metasoft, and FutureNet. Initially, the largest number of micro CADD installations was in electronic design and drafting; but as software development has become more sophisticated, the number of mechanical and architectural installations has increased. However, even with this rapid rate of growth, the revenues generated by micro based systems are a fraction of the overall CADD revenues.

TABLE 2 LEADING VENDORS OF TRADITIONAL CADD SYSTEMS

VENDOR	SYSTEM & APPROXIMATE COST
Applicon Division of Schlumberger Tech. Corp. Founded in 1969 Home office in Burlington, MA	BRAVO, Series 4000 IMAGE & 4000/VLSI $110K-$600K Applications: mechanical, architectural, civil, printed circuit board, & integrated circuit board design & drafting
Auto-trol Technology Corporation Founded in 1962 Home office in Denver, CO	AGW I,II, &III $60K and up Applications: mechanical, architectural, & civil design & drafting
Calma Owned at one time by General Electric Founded in 1964 Home office in Santa Clara, CA	DDM, GDS II, DIMENSION III, TEGAS ENVIRONMENT, T-BOARDS $85K-$250K Applications: mechanical, architectural, civil, printed circuit board, & integrated circuit board design & drafting, & to a lesser extent, mapping
Computervision Founded in 1969 Home office in Bedford, MA	Designer V-X, CDS 3000, 4000, & 5000 $75K-$650K Applications: mechanical, architectural, civil, printed circuit board, & integrated circuit board design & drafting, & to a lesser extent, mapping
Control Data Corporation Integrated Manufacturing Division Based in Minneapolis, MN	ICEM 120 & 800 $45K-$3M ICEM Ergonomic Workstation $25K-$40-K Applications: mechanical, printed circuit board, & integrated circuit board design & drafting
IBM World's largest vendor of computer products & services Home office in Armonk,NY	CADAM, CATIA, CAEDS, 7361 Fastdraft, CBDS 2 $65K-$140K - Applications: mechanical design & drafting, & to a lesser extent, architectural, civil, printed circuit board
Intergraph Founded in 1969 Home office in Huntsville, AL	Intergraph 730, 751, & 780 $78K-$300K Applications: architectural & mapping, & to a lesser extent, mechanical & printed circuit board design & drafting
McAuto McDonnell Douglas Automation Corp. Founded in 1969 Based in St. Louis, MO	BDS/GDS, Robotics (1), & Unigraphics II $95K-$500K Applications: mechanical design & drafting, & to a lesser extent, architectural drafting

Current Uses of CAD/CAM in Various Industrial Sectors

The introduction of economical, powerful microcomputers was a catalyst for the creation of a wider range of mechanical engineering and manufacturing applications. What drove this process? A combination of several factors–the actual change in computing technology, a more integrated approach to CAD/CAM (computer aided design and manufacturing) software, the growing weight of experience, the increasing need for productivity improvements, pressure on suppliers, and increased international competition–undoubtedly contributed. During the period of 1980-85:

> The price of this software tended to match the price of the hardware, and was therefore much cheaper than the turnkey system software. Other factors affecting software during this period were the introduction to the market of several systems developed in Europe that challenged what had previously been a U.S. supplier-dominated market oriented to drafting. The European systems tended to be more oriented toward geometric modelling. It was the period 1980-1985 that solid modellers began to be used, albeit rarely, for everyday industrial applications [Stark 1986, p. 132].

Since 1985, CAD/CAM has moved beyond its first home in the aerospace and automobile industries and into a broader range of manufacturing sectors. Table 3 below summarizes the use of CAD/CAM in various industrial sectors.

TABLE 3 CURRENT USES OF CAD/CAM
Note: CAM includes machine control, material handling, scheduling, planning, testing, & quality.

INDUSTRY	CAD/CAM USES
Aerospace	Fuselage & wing geometry used for aerodynamic and structural analysis; eventually the basis of numerically controlled (NC) programs to produce wind tunnel models. Airframe geometry used to integrate various systems; interference check; perform kinematic analysis of flaps, landing gear, & other moving parts; & position miles of wiring & tubing. Tools, jigs, fixtures, multilayer composites tied to NC machines & robots.
Automotive	3-D model used to model body surface geometry & to analyze curvature for aesthetics & manufacturability. External body shape used to define interior panels & to perform structural, kinematic, aerodynamic, & visibility analyses & to check space allocation for engine, passengers, luggage,etc. Dies and presses designed from geometric computer model. Electronic data transfered to suppliers of tires, windscreens, headlights, fuel sensors, seats, spoilers, & engines.

INDUSTRY	CAD/CAM USES
Ship Construction	Computer geometry used to design hull, to perform static & hydraulic analyses, and to evaluate stability under different damage & loading conditions. Also used to design other structural elements (bulkheads, frames, etc.) & to layout power & environmental systems. Model used to plan most economical cutting pattern for ship plates & to transmit data to NC cutters as well as to provide data to NC pipe fabricators.
Electronics	Manufacturing guidelines coded into software for cost & quality assessment of printed circuit boards. Design database used by fabrication department to generate artwork, board profiling & drilling programs, and connectivity test programs; design database also used by assembly department for component insertion programs and functional tests.
Offshore Engineering	During conceptual design, 3-D models used for structural analysis to assure conformance with international standards; later used for design & fabrication of structural steel with NC plate cutting machines. Also used to layout wiring & piping (hydraulic, ventilation, air-conditioning, fresh-water) and to interference check. Additional software used to calculate pressure & temperature distributions & noise levels in ducts.
Machine Tool & Machinery	Used to produce assembly & detail mechanical drawings, parts lists, electrical wiring diagrams, & panel layouts. Electronic data used for kinematic simulation to check for interference between moving parts & to design gears. Used by machine tool manufacturers involved in flexible manufacturing systems to generate plant layouts.
Clothing& Footwear	Used in clothing design to optimize material cutting process and supply information to NC knife & laser cutting systems. Also used to control decorative sewing machines. Used in footware as marketing tool: images of shoes on monitor photographed & used to test customer reaction. Used to design the complex surfaces of shoe lasts & for programming NC water -jet & laser cutters & plastic moulds. Different sizes are created by a technique called "grading."
Power Generation	Used for a variety of turbine, pump, & compressor applications. 3-D geometry of turbine blades built up & added to the rotor wheel; then structural analysis performed. Also used for NC machining blade dies or electrodes. Apart from blade applications, used in piping layout, sheet metal casings, & interference checking.
Consumer Products	Used to reduce development life cycles by sampling market at conceptual design phase; coloring & light shading techniques used. In packaging, 3-D models used to see how products will look on store shelf; containers analyzed for volume & resistance to shock. Geometry used to design plastic moulds & transfered to mould machines.

Not surprisingly, CAD/CAM has developed through a process of finding particular solutions to special situations; development began on the areas of either greatest need or easiest justification. What has resulted from this piece-meal process: functionally oriented "islands of automation." There is little or no means of data transfer and communication from one island to another, and the islands' databases frequently contain redundant and conflicting data in incompatible formats [Gibbons 1988, p.11].

The latest advances of computer hardware and software technology have invited the concept of "activity centers," comprised of engineering workstations and manufacturing cells and providing support to the organization, to customers , and to product development. Artificial intelligence, in the form of expert systems, is being used in two ways: "as conceptual front ends to CAD systems, to enable 'what if' questions of manufacturability or cost to be asked during the design stage; or as an aid to expand human mental processes and experience (the so-called 'thinking machine')" [Llewelyn 1989, p.298]. The end result is that large manufacturing companies now are attempting to unify their "islands of automation" into their own integrated hardware and software systems. Hence, the concept of CAD/CAM (computer aided design and computer aided manufacturing) is giving way to CIM (computer integrated manufacturing).

Computer Integrated Manufacturing (CIM)

One of the primary motivating forces behind CIM is the need for organizations to be flexible. World-class companies must be able to: produce a variety of products in varying quantities; work with a quality level of zero defects (or close to it); cut cycle times from market identification to delivery to a minimum; consider total life cycle costs; and respond in a timely and economical way to customers' needs. But flexibility and responsiveness cannot be achieved solely through changing plant configuration by adding robots, assembly lines, and flexible manufacturing machining systems.

The ability of an organization to evolve from the present to the future mode depends on a suitable conceptual definition of the organization. Also important are the relationship between products and processes, the configurations of information systems and CADD/CAE, and the systems available from vendors. Computerized tools and systems must interact with an evolving product model. Each computer representation describes the product at a particular level of abstraction and at a particular point in the life cycle. A representation may include data specific to one or more life cycle activities or project participants (i.e., graphical, functional, logical, and physical representations.) Additionally, a distinction must be made between the physical factory and the logical factory, just as maximizing the usefulness of CADD requires that output be viewed as three dimensional models and not as two dimensional drawings. According to the US National Research Council, CIM occurs when [qtd. in Gibbons 1988, p.10]:

- All of the processing functions and related managerial functions are expressed in the form of data.
- This data is in a form that may be generated, transformed, used, moved, and stored by computer technology.
- This data moves freely between functions in the system throughout the life of the product.

There are numerous descriptions of product lifecycle. Most include engineering, product administration, manufacturing, and product support. Rarely does the output of one step in the product lifecycle become the the entire input of a succeeding step. Rather, there are various iteration steps, feedback loops, and multiple sources and uses of data. Figure 2 on the following page is a two dimensional attempt to represent what is more like a three dimensional process.

In itself data exchange is not an enterprise integrating mechanism. Data exchange propagates pieces of product data which are both redundant and inconsistent. There are several problems associated with data exchange among computer systems and tools/equipment. Consider "A," a receiving system, and "B," a sending system: 1) the definition of the required data–content and form–is a function of "A"; 2) the definition of the of the form and content of the data to be transfered is a function of "B"; 3) the data required by "A" may have more sources than "B" alone; and 4) transfers are incomplete because of differences in the functions of "A" and "B" and in the mappings used between the internal representations of each system and the constructs available within the transfer mechanism. Achieving the desired levels of automation and integration depends on the ability to manage the information resource well. That reality leads to one conclusion: effective management is dependent upon the development and application of standards.

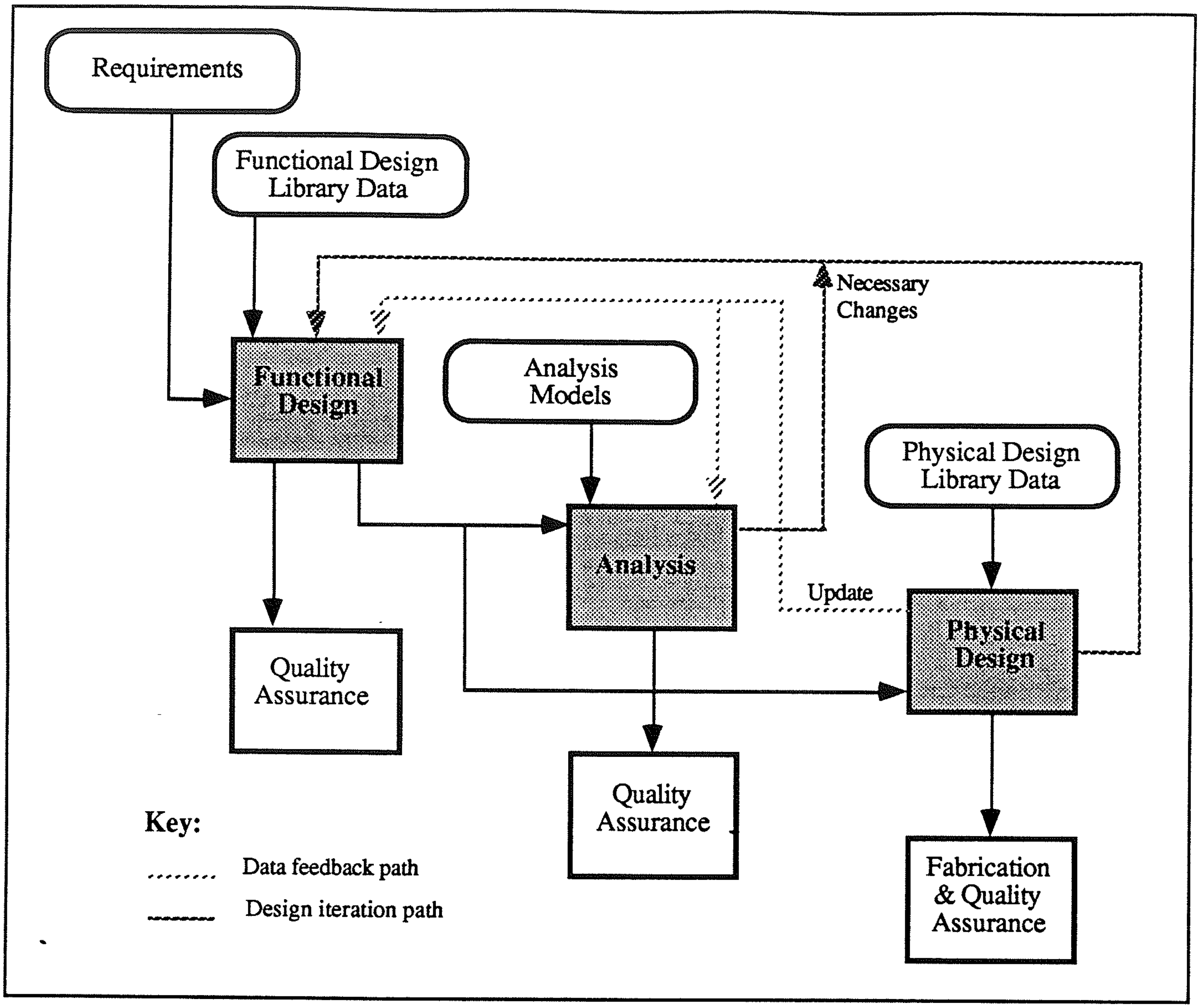

Figure 2 - MANY SOURCES & USES OF CIM DATA (Adapted from Gibbons 1989, p.11)

Industry standards are consensus solutions to common problems. A standards framework (sometimes called "architecture") creates a structure that supports coordination and development of data integration techniques. Many international organizations are working on the development of standards. Table 4 below is a partial list of these organizations and their primary activities.

TABLE 4 ORGANIZATIONS for STANDARDS

ORGANIZATION	ACTIVITY
International Organization for Standardization (ISO) Geneve, Switzerland	Creating a reference model for the Open Systems Interconnection (OSI), a layered architecture for communication. The OSI model is the basis for MAP (Manufacturing Automation Protocol), a tool to study & organize interprocess communications. Also drafted STEP (Standard for Exchange of Product Model Data).
IGES/PDES Organization Gaithersburg, MD	PDES (Product Data Exchange Specification), managed by the National Bureau of Standards, supports ISO activities in the U.S. IGES (Initial Graphic Exchange Standard), also a U.S. standard, creates rules for the exchange of mechanical design data between CADD systems.
Product Definition Data Interface (PDDI) Wright-Patterson Air Force Base, OH	The U.S. Air Force funds projects to study data requirements for the replacement of engineering drawings with electronic data sets.
Computer Aided Manufacturing International, Inc. (CAM-I) Arlington, TX	Sponsored a joint research & development activity, EAP (Electronics Automation Program), to identify required contents & preferred form for product & process data needed for automated manufacture of electronic products. Also identified five functional elements of CIM.
Computer Integrated Mfg Open Systems Architecture (CIM-OSA) Project of ESPRIT (European Strategic Prog. for R & D in Info. Technologies) Brussels, Belgium	Through AMICE (European Computer Integrated Manufacturing Architecture), attempts to develop an open system architecture of common rules & properties. Three generic models are identified: enterprise activity, information management, & CIM implementation.

Computer Aided Manufacturing-International, Inc., a non-profit organization owned by companies interested in CIM and supported by governmental, industrial, and educational groups from many countries, proposes a CIM architecture containing five basic elements: 1) management; 2) function and activity; 3) information; 4) computer systems; and 5) physical configuration [Gibbons 1989, p. 11]. Each of these categories contains subsets.

For example, the management segment breaks down into planning, policy, organization, responsibility and interrelationships, performance measurement and financial reporting, and management of technology. In additional to developing an appropriate architecture or framework, four key technological ingredients are required for CIM. These are the ability to manage and access data, the capacity to distribute data over a network of different vendors' computer systems, the availability of part geometry, and software to assist interfacing to the system [Stark 1986, p. 149]. (For more information on the CAM-I approach to CIM architecture, the reader is referred to a series of articles in *CIM Review* starting with the Winter 1989 issue.)

As yet, computers have not become substitutes for good management. The success of a CIM approach is heavily dependent on management commitment and on-going support. And the pressure on world-class firms to produce a variety of high quality, cost effective products in a minimal time frame seems to assure the continuation of the CIM approach.

CADD/CAE in the AEC INDUSTRY

The introduction of accessible CADD carries the possibility of creating profound effects on individual engineering and construction companies. Until recently, architecture and civil engineering were the backwaters of software development. In the 1970's, reduced software and hardware costs, additional capabilities, and increased user-friendliness encouraged wider use of CADD. CADD software appeared to evolve pragmatically, "without a strong theoretical underpinning" [Eastman 1989, p.289]. Ten years ago, according to Eastman [p. 289]:

> ...architectural computer-aided deign was dominated in the USA by Intergraph, which had recently surpassed Autotrol as the CAD system company with the largest sales in the architecture, engineering and construction (AEC) market. They held about 40% of the AEC market. Digital Equipment PDP-11s were just being displaced with the first 32-bit minicomputer, the VAX 780. The per seat cost of CAD was typically about US$100,000. Two or three shifts of operators were necessary to justify the capital investment.
> ...Ten years ago, less than 10% of architectural offices were using CAD, and those that were corresponded to the largest firms.

The introduction of the super-minicomputers in the late 1970's and the super-microcomputers in the early 1980's meant that CADD was an affordable tool. And now CADD software designed to run on personal computers has made CADD available to even very small companies. "The number of alternative CAD systems available for use by architects has increased over the last ten years. A shakeout in minicomputer-based systems was complemented by a new generation of PC-based systems. AutoCAD has replaced Intergraph as the de facto standard" [Eastman 1989, p.290].

With several notable exceptions, which appear below, until recently most AEC designers have been content to use CADD for 2-D drafting [Crosley 1989, p.110][Ibbs 1989, p.9]. This can be explained partially by the fact that many systems are still cumbersome, difficult to install, and inadequate as drawing tools [Witte 1989, p.107]. The usual requirement that drawings be created in terms of Cartesian coordinates or in geometric "primitives," necessitates a significantly different way of viewing the conventional drawing process, a method which has evolved over two-hundred years. Additionally, computer programmers may have carried over too much of the thinking surrounding manufacturing CADD into building related software. Even a program like AutoCAD frequently must be used with a companion, "overlay" program such as AEC, DCA-10, or KETIV, in order to make the basic program more user friendly [Whitley 1989].

The real benefits of CADD appear to emerge in integrated companies which have control over both design and manufacturing or design and construction. The following section describes the efforts of three AEC firms, each of which has made a serious commitment to integrate CADD and other information (computer) technologies into its operations.

Some Example Companies

Stone & Webster Engineering Corp. specializes in large, complex power plants. When deciding to pursue an computer integrated approach to design and construction, Stone & Webster selected the IBM mainframe environment, largely because of the number of components contained in each project. The company is using an IBM 3090 mainframe computer located in its Boston headquarters with links to regional offices, clients' offices, and jobsites. The graphics workstation, an IBM 5080, is used in conjunction with dedicated terminals and PC2's.

Stone & Webster has adapted several off-the-shelf software packages from IBM and has created its own program, STONE*link* ®, to join graphics and database data. The firm employs an IBM 3-D, full scale modeling application called CATIA, developed in France by Dassault Systems. It also uses IBM's CADAM, created at Lockeed Corp., as a drafting tool. The 3-D models are used for GTSTRUDL structural analysis and defining structural steel sections, for locating piping anchor points, for interference checking, for generating bills of materials, and for developing construction sequence models. An IBM relational database, DB2, interfaces with graphics, plant operation, and plant engineering data. Additionally, the company has created experts systems to query the database through an IBM expert shell, ESE. Table 5 lists some examples of the information stored in the database [Reinschmidt 1989, p. 7].

TABLE 5 STONE & WEBSTER'S DATABASE

COMPONENT	GRAPHICAL DATA (CADAM/CATIA)	NON-GRAPHICAL DATA (DB2)
Plant Schematic	Object Identifier	Object Identifier
Diagram	Part Number	Specification Number
Drawing	Location	Purchase Order Number
Floor Plan	Connectivity	Drawing Reference
or	Flow Direction	Vendor Data
Product Drawing	Dimensions	Spare Parts Inventory
	Orientation	Maintenance History
		Preventative Maintenance
		Environmental Data
		Quality Data

Starting in 1984, Stone & Webster's management apparently made a strong commitment to computer integration. The company's Advanced Systems Development Group has recognized the need for computer systems that create bridges between commercially available application packages. The firm developed STONE*link* ® and STONE*view* ®, which connects CATIA or CADAM graphical data with the DB2 relational database on the PS2. The firm uses these programs in-house and also markets them, along with consulting services, to others in the AEC industry.

Bechtel Power Corp. in Gaithersburg, Maryland began development of its own CADD package in 1982 after determining that none on the market met the company's specific needs. The system, 3DM™, is marketed by Bechtel Software, Inc. in Acton, Massachusetts. Originally, Bechtel layered 3DM™ over an Intergraph CADD system. The program currently has four possible hardware configurations: 1) Intergraph workstations connected to Intergraph VAX systems (VAX is a mini-computer manufactured by Digital Equipment Corp.); 2) personal computers connected to either an Intergraph VAX or standard DEC VAX system; 3) an Intergraph Unix workstation in a stand alone mode; or

4) a combination of the previous three types. Either DECNet or Ethernet communication packages can link the workstations.

3DM™ consists of a basic core module and five others. The core module contains the software to support the various discipline modules as well as the functions that are common to all modules, including model manipulation, interference detection, and bills of materials. The other modules are piping and equipment; piping and instrument diagram (P&ID); structural steel and concrete; electrical cable tray and conduit; and HVAC (heating, ventilating, & air-conditioning) ductwork. A variation of one of these modules, SETROUTE™, is a PC based cable and raceway tracking and scheduling system which is marketed separately. Another Bechtel product, WALKTHRU™, is a realtime animation program.

Additionally, Bechtel has been working to interface 3DM™ with Oracle™, a relational database developed by the Oracle Corp. One goal is to transfer the constructive solids geometry (CGS) of the CADD primitives to the database; when this is accomplished, the database will contain a geometric description of each of the three dimensional model components. Currently, 3DM™ can load attribute, location, and orientation data into the Oracle™ database. Bechtel system designers see change control as one key capability of this link.

Black & Veatch, a consulting engineering firm from Kansas City, MO, has developed an in-house integrated relational database and 3-D CADD program. Since 1979 the company has invested more than $30M to design, program, and test its POWRTRAK system. The company found that no commercially available system met their needs and, additionally, that dependence on vendors for system and hardware enhancements was something to be avoided.

POWRTRAK, is capable of producing off-the-shelf powerplant designs, shop drawings, and material take-offs [Post 1989, p.32]. All project data are developed and maintained in a single data file; any changes affecting the project are provided to all functional areas. Additionally, the information is the data base is available to plant operators and maintenance workers.

Other Applications

In addition to the examples mentioned above, CADD has proven useful in several other applications–three dimensional modeling, restoration, and integrated design and building component manufacturing.

Computer aided models (as contrasted with models made of cardboard, balsa, plastic, etc.) enable designers to explore options freely. Three-dimensional models can be used to: shade and texture surfaces; show gradations of color; and depict reflection and degrees of translucency. These models also provide for the introduction of time and motion. Programs like Bechtel's WALKTHRU™ simulate a walk around and through a building. Time lapse permits consideration of changing sun angles according to the time of day, season, and latitude.

One very promising area to emerge in the past few years is the use of CADD in building renovation and restoration. To document existing conditions and develop a basis for restoration, Interactive Resources, Inc., a Richmond, CA, architectural firm uses photographs and a digitizer to enter information into the firm's CADD system. The Oroville Redevelopment Agency retained the company to create a scheme for renovating the town's historical commercial district. (Oroville has a population of 10,500 and is approximately 160 miles northeast of San Francisco in California's Central Valley.) Photographs of Oroville's fifteen historic storefronts were digitized and the computer dimensional information was checked against field measurements. Designers used the computer model to create demolition drawings and, after electronically removing the areas to be demolished, to develop design drawings. Interactive Resources, Inc. found that dimensional checking consumed the time that the digitizing saved; however, after the computer model existed, revising and going through "what-if" schemes were much simpler than manual methods [Butt 1989, p.117].

Videographic methods and computer data processing also can facilitate documentation and design in restoration projects. The technique works through "frame grabbing." The videotape record provides a library of images of the site. One of these video signals, which is in line (raster) form, is converted to the computer's digital signal, which is in dot (pixel) form. The computer image, replicating the video image in color and resolution, is stored in the computer's memory structure for future reference and manipulation. Through the use of frame grabbing techniques, a wide variety of information from many media sources—

sketches, slides, photographs, video—can be merged into a single environment [Jones & Kennedy 1989, p.97]. Designers are able to recreate the colors, structure, and form of buildings to reflect their original appearance. Dimensional analysis can be performed based on plane geometry constructs; some systems, such as VideoCad, are capable of determining dimensions directly from the digital images. However, due to computer hardware resolution problems, the planar techniques are not sufficiently refined to produce accurate as-builts.

In addition to the integrated design and construction capabilities previously mentioned—interference checking, material take-offs, environmental performance calculations, and facilities maintenance/management—some suppliers of building products are experimenting with CAD/CAM-like operations. Several examples using CADD linked to computer controlled machines are: 1) wooden trusses: members sized, bills of materials generated, and lumber cut and assembled; 2) modular (mobile) homes: floor, wall, and ceiling panels designed and penetrations cut; and 3) automated stone-cutting: shop drawings generated and stone cut (some stone cutting of Gaudí's Sagrada Familia in Barcelona is being accomplished with an automated saw) [Wilson 1989, p.125]. Other companies are generating steel fabrication drawings electronically from structural engineers' design drawings. What is surprising is not the use of CAD/CAM in the AEC industry, but rather its lack of use. Fragmentation and organizational issues account more for this condition than lack of adequately developed computer technology. (A later section addresses this subject in greater detail.)

Research Activity

Researchers within the AEC community have been concentrating on using expert systems and on incorporating database systems with CADD. Expert system research has moved in several different directions: overlays to facilitate the use of existing computer systems; specific applications; and synthesis of the various stages of design.

About the same time Stone & Webster and Bechtel were beginning their exploration of computer software, the Artificial Intelligence Center at Boeing Computer Services, Seattle, was working on a overlay to an existing CADD program. The BCS prototype expert system serves a function similar to the overlay programs mentioned in conjunction with AUTOcad; the expert system manages access to the CADD program's various modules. It monitors the flow of information between the users, application programs, and databases and modifies the format of the data depending on the context. A substantial amount of effort is being directed to this type of expert system in manufacturing, and further development in the AEC industry seems likely.

Other expert systems result in very specific applications. British researchers have worked with UK building component manufacturers to produce two such systems. The first is a program for laying out brickwork cladding. Designers use an AUTOcad graphics package to outline the face geometry and to position each face element; the expert system works in conjunction with the graphics to provide information about possible expansion joint positions and to suggest improvements. The second expert system involves metal stud partitions; it helps determine which configuration of gypsum and metal studs meets structural, acoustical, and fire resistance design criteria most economically. Researchers view these expert systems as prototypes leading eventually to knowledge-based design systems that aid in the design of entire buildings [Cornick & Bull 1987, p.123].

There is a need to supply designers with conceptual design tools. Detail design is generally less complex and more constrained than design evaluation and synthesis. Basically, two dimensional CADD programs are drafting tools; but three dimensional programs open up many possibilities for the important "what if" scenarios in conceptual and preliminary design. Expert systems that link analysis analysis, visualization, and early design evaluation are being explored. However, the task of linking expert knowledge to geometric models is far from trivial. Thus far, most research for these systems is in its preliminary stages, focusing on how to connect conceptual design, analysis, and evaluation. Some prototype programs have been developed, including one that compares building layouts with local building codes [Rosenman & Gero, referenced in Gero & Maher 1987, p.87] and another that creates a preliminary construction site layout based on optimal spatial relationships [Tommelein 1989].

TECHNOLOGICAL & ORGANIZATIONAL IMPLICATIONS

The previous two sections of this paper have addressed the development and use of CADD/CAE within the AEC industry and others, like manufacturing. In the early 1980's, some AEC firms decided to plunge into the potentials and problems of integrated computer programs; other companies still wrestle with two dimensional CADD systems. But technology itself does not impede the adoption of CADD/CAE [Schnur 1988, p.3]:

> ...contemporary computer systems are much more advanced than what is required for achieving our goal. A decade ago, storage, speed, and interconnectability were prevailing obstacles to implementation. Thus, brute force processing was an inhibitor as was system performance and reliability. Today's gigabytes and multiMIPS combined with selective network structures and data management strategies can provide more than is needed...

If technology is not a limitation, what are the roadblocks to CADD/CAE implementation? The final section of this paper investigates some of these barriers and outlines significant organizational issues influencing CADD/CAE.

Roadblocks to CADD/CAE Implementation

At the most fundamental level, limited conceptual understanding of both organizational and technical issues has blockaded implementation and successful use of integrated CADD/CAE systems. Research into the use of CADD/CAE and CIM in manufacturing sheds light on these issues. In three separate studies, Adler, Badham, and Wolf & Manske, investigated CADD in U.S., Australian, and West German firms, respectively. These authors found that few companies were willing to make the procedural, structural, and cultural changes necessary to achieve design and manufacturing integration. As a result, "...few engineers using CAD are observed to actually work on new and innovative designs, few CAD designers actually spend more time talking to production, and few improvements are identified in design-to-market life cycles..." [Majchrzak and Salzman 1989, p. 177].

In a different survey of 350 operations managers, manufacturing engineers, and vendors, investigators found capital justification and top-management understanding to be the most significant barriers to implementation of CIM [Smith & Michaels 1989, p.40]. Often cost accounting practices do thwart capital justification—tieing revenue increases to computer initiatives is difficult. Accounting systems do not capture a sufficient level of detail to measure the effects of improved quality control and design/manufacturing flexibility. Additionally, no satisfactory mechanism exists within the justification process to recognize the competitive consequences of making an investment in computer integration versus not doing so. The survey also indicated that managers have unrealistic expectations and concerns regarding CADD/CAE. This can be explained partially by the fact that many managers and/or executives do not come from technical fields and may be plagued by fear of the unknown. They also may be members of a pre-computer-literate generation.

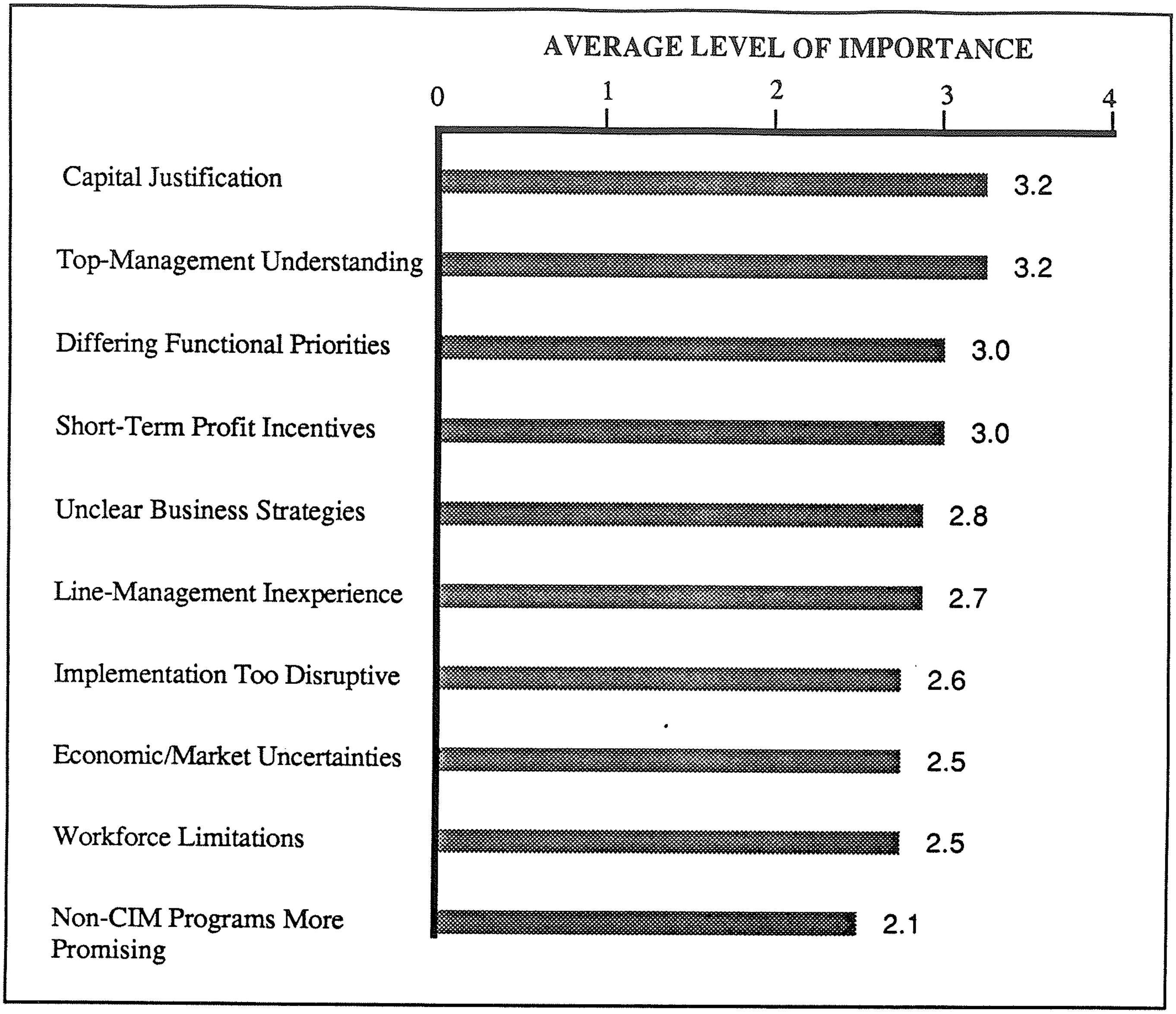

Figure 3 - ROADBLOCKS TO CIM IMPLEMENTATION
(Source: Smith & Michaels 1989, p.40)

However, even technically oriented managers face new organizational considerations and often adopt minimalist approaches. Just getting the technology in place seems to be a major hurdle, and the "tactics of technicalizing" often overshadow organizational change factors. In other words, problems regarding file management warrant greater consideration than more complex, conceptional issues surrounding implementation. At an even more fundamental level, there may be some doubt on management's part that integrated computer systems can capture the essence of what makes an organization tick. For the sake of discussion, this essence is referred to as *tacit knowledge.*

The problem of capturing tacit knowledge is both an organizational and technical issue. According to Michael Polanyi, who developed the concept of tacit knowledge, knowledge is shaped through experience. We develop awareness of the whole, integrating the particulars, without being able to identify the particulars [Rasmussen, Eriksen, & Hansen in Rader et al 1988, p. 76]. So the first task in implementing an integrated computer system is to identify the organizational particulars; the second is to develop a computer system which captures these particulars.

Organizational Changes Ahead

Making this process more difficult is the fact that computers themselves, integrated or otherwise, are changing organizations and the way we work. We just are beginning to comprehend the consequences of computerization. Zuboff observes that, over the last century, the more rational elements of executive work have been carved out, thereby creating clerical positions first and middle management slots second [Zuboff 1988, p.107]. Much work considered clerical (routine) has been automated already. This computerization has had profound effects: "As information technology restructures the work situation, it abstracts thought from action. Absorption, immediacy, and organic responsiveness are superseded by distance, coolness, and remoteness" [Zuboff 1988, p.75]. Even in routine jobs, computers have forced workers to think more abstractly, requiring a new set of competencies.

Now technology exists that can take us beyond the routine. Computer programmers are attempting to automate less rational processes like design and management. How will the use of computers affect these areas? Several researchers have suggested that there are short term (up to six months after the the starting point of using computers), medium term (six months to one & one-half years), and longterm (four to five years) effects [Rasmussen, Eriksen, & Hansen in Rader et al 1988, p. 79]:

> In the short-term we are typically dealing with technical problems of adaptability of the new system to existing requirements.
> The medium-term is related to health and safety problems (stress, visual problems etc.).
> The long-term consequences are related to the change in the way designers use their imagination and logic abilities.

Though the time-frame suggested may not be accurate, the concept seems valid. The use of three dimensional CADD models may be more limited by our ability to conceptualize the significance of these models than by cost or computer hardware barriers.

Many questions regarding the implementation of integrated computer systems remain unanswered. Will computers' need to rationalize eliminate the subjective elements of design and management? How can tacit knowledge be rationalized, when by definition tacit knowledge defies rationality? And what kinds of organizations will evolve from these efforts?

Existing skills (including tacit knowledge) and the social context are very important. Several authors suggest that a high degree of social integration is necessary to maximize the usefulness of integrated computer systems, along with an awareness that these systems will have a fundamental impact on work organization. Speaking about the influence of CADD on British architectural firms, Selby notes [1984, p.151]:

> To effectively use the benefits of CAD the practice may have to perform a full re-appraisal of management roles and traditional hierarchies and demarcations. Professional barriers and departmental separations, where they exist, may all have to be broken down, or at least reduced, in the rush for effective CAD. Because of the integration of work and information flow demanded by CAD there may exist real obstacles in some of the traditional separations between designers and draughtsmen, architects from quantity surveyors from engineers. All should become more united by one common computer model without any particular professional obligations, loyalties or affiliations.

Zuboff continues the theme. She notes that integrated computer systems have the potential to whittle down hierarchies, but that transforming changes stem from a series of managerial choices {Zuboff 1988, p.285]:

> When a plant manager asks, 'Are we all going to be working for a smart machine, or will we have smart people around the machine?' he [she] portrays two divergent scenarios. In the former, the line that separates workers from managers is sharply drawn. Workers are treated as laboring bodies, though in fact there is less that their bodies can contribute in effort or skill. As workers become more resentful and dependent, managers react by sinking more resources into automation. In the alternative scenario, both groups work together to forge the terms of a new covenant, one that recasts the sources and purposes of managerial authority.

Obviously, reducing hierarchical structures means changing traditional power bases, and whether this will happen remains to be seen. Only one basic truth seems to stand out: those firms which become involved in CADD, CAE, and/or integrated computer system should be prepared to experience some profound changes.

CONCLUSION

This paper has attempted to shake off "the natural attitude" that inhibits us from realizing the true potential of CADD and CAE. The complete impact of CADD/CAE on the architectural, engineering, and construction industry will be felt only when practitioners understand the conceptional differences between the old and new way of doing things.

This paper has attempted to show how increased interest in computer information technologies may affect architects, engineers, and contractors. It has explored the development of CADD and CAE in both the AEC industries and others, like manufacturing, and has investigated what the most advanced users of CADD and CAE are doing within the AEC industry. Finally, it has singled out some possible technological and organizational implications of these new computer systems. This writer hopes that the readers' minds both have been impressed with the distance CADD/CAE has come and have been challenged to participate in the changes which lie ahead.

GLOSSARY

Artificial intelligence: the concept that computers can be programmed to make decisions and learn from previous experience.

ASCII: acronym for the American Standard Code for Information Interchange, a computer standard representation of alphanumerics and punctuation as binary numbers.

Boundary representation, Brep, B-rep: used in 3-D computer models to depict all of the faces, edges, and/or vertices of a solid object.

CAD/CADD: computer-aided design/computer aided design & drafting.

CAD/CAM: computer-aided design/computer-aided manufacturing.

CAE: computer-aided engineering.

CIM: computer-integrated manufacturing, the integrated computerization of manufacturing functions.

Competitive advantage: a company's position, based on superior performance, that separates it from its competitors.

Competitive strategy: a way of achieving competitive advantage through choice of: 1) market segments, 2) product/service offerings, 3) selective pricing and fundamentally different cost structures, 4) contractual flexibility, and/or 5) technology.

Constructive solid geometry (CSG): a method of developing 3-D models by representing objects as additions or subtractions of simpler solid objects.

Data base: collection of interrelated data stored together without redundancy and serving multiple applications.

Expert system: computer program that is modeled after the decision making process used by a human expert.

Initial Graphic Exchange Specification (IGES): system recognized by the National Bureau of Standards for transferring graphic information between computer programs.

Model: an object or process represented as a single unified entity.

Primitive: a simple geometric element such as a line, arc, circle, etc.

Orthogonal projection: views of an object are constructed by extending perpendiculars from points on the object to the plane of projection.

Swept object: a solids primitive created by extruding a two-dimensional object along its axis.

Three-dimensional primitive: set of points, lines, curves or surfaces that define a single, complete and unambiguous object.

Strategy: policies adopted by a company that support overall mission; a course of action.

Technology: a practical application of scientific or engineering knowledge; more broadly, an activity using materials and labor to create a commodity.

Value chain: all possible components of an activity which may contribute to a product or service's profitability.

Vertical integration: a means of expanding a company's product or service position by changing the boundaries of the firm's activities.

Wire frame: a 2-D or 3-D projection or model which is represented by its edges.

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