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Evaluating the Use of CAD Systems in Mechanical Design Engineering

David C. Robertson
Thomas J. Allen

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MASSACHUSETTS
INSTITUTE OF TECHNOLOGY
50 MEMORIAL DRIVE
CAMBRIDGE, MASSACHUSETTS 02139

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Abstract

Despite the importance of and our long history with Computer-Aided Design (CAD) systems, our understanding of the systems is limited. The academic and trade literature provides little guidance on what organizational actions are necessary to utilize CAD systems for maximum benefit.

To understand the role CAD systems are playing in the design engineering processes of different companies, field interviews were conducted at twelve companies. Design engineers, managers, CAD support personnel, and others were interviewed to understand the use of CAD systems for mechanical design engineering.

The result of the field research is the conclusion that managers view CAD technology in one of three ways: as physical capital, as supporting or extending human capital, or as enabling improvements in social capital. Further, the value received from the technology will depend directly on how managers view the technology. Managers who see the systems as physical capital (i.e. electronic drafting boards) will receive some benefit; managers who view the systems as enabling improvements in social capital will receive the greatest benefit from the technology.

The characteristics of each of the three views of CAD technology will be discussed, as well as the barriers that prevent companies from realizing the full benefit of CAD technology.

Introduction

In recent years, industry has focused a considerable effort on reducing product development times.. Many believe that the appropriate use of Computer-Aided Design (CAD) systems may aid significantly in achieving this goal. Many companies have made large expenditures on CAD systems- expenditures have reached $100 million for a single company's hardware and software. The market for CAD/CAM hardware and software was over 17 billion dollars in 1987 and is expected to grow to 39 billion by 1991 [28].

There has been some debate, however, over the benefits of CAD systems [13]. While many organizations have made large investments in CAD technology, some of these organizations do not believe their money was well spent. These organizations are not seeing the benefits they expected from their systems.

In the following sections, the results of an investigation into the uses of CAD systems at twelve manufacturing companies are reported. The goals of the research are to understand how the systems are used, what difficulties occurred in implementing the systems, and what benefits resulted. In the next section, an introduction to CAD systems is presented, followed by a brief review of the current literature relating to Computer-Aided Design.

CAD Systems

Introduction

CAD systems are defined in this paper to be those computer tools that support the design and design engineering processes. This definition thus includes computer tools normally classified under Computer-Aided Design, Computer-Aided Drafting, and Computer-Aided Engineering (CAE). The greatest use of these tools is in the support of mechanical design and engineering [20]; it is that area of application that will be addressed in the present paper. More information about the features and functions of such software can be found in [4],[20].

CAD systems can potentially lead to many important benefits for organizations. For example, CAD systems can potentially reduce the length of the product development cycle and improve relationships with both vendors and customers. The literature provides many descriptions of CAD applications that have helped to reduce the product development time ([3],[5],[6],[14],[23],[25],[27]). A shorter design cycle allows companies to respond more quickly to competitive challenges, incorporate newer technology into products, and charge higher prices for unique features.

CAD systems can also help improve a company's links with its vendors and its customers [7],[11]. For example, one airframe manufacturer provides major customers with a CAD terminal. If a problem occurs in the field, maintenance personnel can access the CAD design file and either (1) communicate by phone with the manufacturer's support personnel (who can access an identical CAD file) or (2) make comments on a CAD file and send the file electronically to the manufacturer. In either case, communication between the manufacturer and its customers is faster, there is less ambiguity in the information communicated, and there is much less travel required of the manufacturer's support personnel to customer sites.

Yet despite the potential benefits of CAD systems, our understanding of the systems is limited. In the next section, a review of the literature on the use of CAD systems in organizations is presented.

Research on the Impact of CAD Systems

The academic and trade literature provides little guidance on what organizational actions are necessary to utilize CAD systems for maximum benefit.

The studies in the literature fall into three categories: "competition" studies, social impact studies, and case studies.

In the "competition" category are studies which test the performance of CAD systems against drafting boards. Such studies show productivity gains from 25% to 350%, depending on the complexity and repetitiveness of the task [19], and on the type of task. Many managers interviewed for this study report, however, that such gains do not always occur in their own companies.

Studies of the social impact of CAD systems have produced mixed results, some finding for enrichment of jobs [1], and others finding that CAD leads to "de-skilling" [10]. Some studies even show both effects occurring [18],[26]. These mixed results were also seen in field interviews- different companies report different changes in jobs. Some reported that the work had become more repetitive, others stated the opposite.

In the third category of research, case study research, companies report the productivity gains from implementing a certain system or application. For example, Swerling [24] reports that the use of computer tools cut the development costs for the IBM 3081 computer by 65%. Bull [5] reported that CAD/CAM improved productivity for product development by 150%. Chrysler estimates that computer tools will cut the development cycle for new cars from five years to four or less [14]. Kodak [12] linked product designers and tool designers through a common CAD system and were able to develop the "Fling 35" camera from project start to shipping approval in 38 weeks. They estimated that this CAD system helped them reduce development costs by 25%.

Unfortunately, with few exceptions, this third category of research provides managers little insight into how to achieve similar gains in their own organizations. The studies in this stream of research focus largely on the specific characteristics of the new technology, and ignore the other technological and organizational changes that must be made to utilize the technology to full advantage. With few exceptions (e.g. [15],[23],[26]), it is not clear how the results achieved in these studies could be repeated in other organizations.

It is important to note that the large gains reported in the case study literature are hardly guaranteed- some managers believe that the introduction of CAD systems has hurt productivity (cf. [13]). If the productivity gains of CAD systems are mixed, it is less likely that the negative impacts would ever be reported in the literature. Thus we cannot count on the literature to accurately reflect the average company's experiences with CAD systems.

The reason for the lack of convergence in the social impact studies and managers' disagreement with case study results is that CAD systems do not necessarily *cause* any changes to occur to the structure or processes of an organization- they only enable changes. The eventual use of a CAD system is as much a result of managerial decisions, individual predispositions, and organizational environments as it is of the features of the system. Thus different organizations can (and do) use the systems quite differently. CAD systems are a complex technology, and their application in organizations tends to reflect the characteristics of the organization as much as the features of the technology [2],[18].

Different Perspectives on the CAD Investment

The concepts of physical, human and social capital that are defined and developed in this section will be used to analyze the observational data from the field. Physical, human, and social capital can be seen as resources in the product development process. A good manager will develop and use each to its maximum advantage. Physical Capital comprises the machines and equipment that are used to add value to a product, or allow a product to be developed more efficiently (i.e. more quickly or less expensively). The cost and value of this type of capital are relatively well understood by managers. Human Capital comprises the skills and knowledge of a company's workers that allow them to add value to a product during its development, or to develop a product more efficiently. Managers are usually willing to pay the cost of developing this capital, even if they cannot quantify the value to be received. For example, managers and companies will release employees for weeks, months, or even years so that they can attend seminars, classes, or degree programs. This is done with the implicit assumption that the employee is worth more to the company upon returning from such as experience.

The third type of resource is Social Capital [9]. Social capital resides in the relationships between individuals that allow them to add value to a product during its development or develop a product more efficiently. Social capital is not a property of the individuals in an organization- it is a property of the relations among individuals. As with physical and human capital, social capital is not completely fungible- the development of a certain type of social capital may be productive for certain tasks, but have no effect or be harmful for others. Managers often do understand that the ability of their employees to work together to accomplish goals has a great deal of value, and that developing social capital can return large benefits. Many organizational actions such as forming ad hoc teams, creating liaison roles, or adopting a matrix structure are undertaken to improve social capital.

Research Method

To understand how organizations are using CAD technology, field interviews were conducted at twelve manufacturing companies. The twelve companies produced a wide range of different products, including college rings, plastic bottles, jet engines, airframes, copiers, and automobiles. The goal of the interviews was to understand:

- The nature of the design engineering process,
- The coordination demands of the design engineering process,
- The features and capabilities of CAD systems,
- The changes in the process and structure of the organization that have occurred since the introduction of CAD technology,
- The nature of the companies' management and their attitudes toward CAD systems, and
- The potential future changes that are enabled by the systems.

Interviews were conducted with a broad cross section of roles, including design engineers, managers, CAD support personnel, and others. A total of 46 design engineers, 32 managers, and 22 CAD support personnel were interviewed in the 12 companies. In addition, 39 individuals from other groups which assisted the design engineer in his or her work (such as analysis or manufacturability groups) were also interviewed. An average of two days was spent in each company.

The goal of the interviews was to understand the design engineering process and the role computer tools play in it. Investigating the use of computer tools throughout the product development process was outside the scope of the research; it was decided to focus solely on the design engineering phase of the process.

It was also decided that the research should focus on the design engineering of the ten companies developing complex products. Significant differences were noted between simple and complex product development processes. Thus the conclusions reached in this paper will not necessarily apply to the design engineering of all products.

The Design Engineering Process

Many authors have characterized the product development process as passing through a number of stages. Myers and Marquis [21], for example, describe five stages: recognition, idea formulation, problem solving, solution, and utilization and diffusion. Roberts and Frohman [22] call for six by designating Myers and Marquis' "solution" "prototype solution" and adding "commercial development" as an additional, and we might add, a very important phase. Clark and Fujimoto [8] return to five phases, based on the automobile development process: concept generation, product planning, design engineering, process engineering, and production. Building on these earlier formulations, we will present another characterization of the product development tailored to the current research. The goal is to build a general model of product development which corresponds well to the many different complex product development processes studied.

In the products studied, the product development process can be described by six phases. In the Recognition phase, the company identifies a need for a new product or a potential application of a new technology. In the Idea Formulation phase, a design specification for a new product is developed. In the Design Engineering phase, this specification is translated into a set of detailed drawings so that a prototype product can be built. In the Prototype Refinement phase, defects are removed and additional improvements may be made to the prototype. After the final version of the design is decided upon, the Process Engineering phase begins. In this phase, the detailed design specifications are used to create a process design, which may include flow charts, plant layouts, tool and die designs, etc. When this phase has been completed (as judged by the success of a pilot production run), the Utilization and Diffusion phase begins.

This research focuses on the Design Engineering phase of the product development process. In the next section, the observations from these interviews are presented.

The Field Interviews

The Design Engineer's Job

Engineers in the design engineering phase of product development are often organized functionally around either parts of the product or types of analysis (cf. [17]). Design engineers may be assigned a part or group of parts and are then responsible for completing the design of those parts (and are often responsible for the parts during the later phases of product develpment). The organization of a typical work process (for the companies studied) can best be described by an example.

The design engineers responsible for the engineering of a gas turbine engine are usually organized around the different parts of the engine- the compressors (which compress and heat air), the turbines (which drive the compressors), the burners (which mix compressed air with fuel and ignite the mixture), the shaft and bearings (on which all rotating parts turn), the static structures, and the overall systems (for circulating air, fuel and oil around the engine). The engineer responsible for the engineering of a turbine blade would report to the manager of a Turbine group, which is responsible for all parts in that area of the engine. This engineer would work with the engineers responsible for the parts adjacent to his: engineers in the Static Structures group, the Shaft and Bearings group, the Systems group, and the group responsible for the next and previous stages in the engine (possibly a Compressor group and the Burner group).

In addition, this engineer may be required to work with many other groups. For example, for the design of a turbine blade, the design engineer must work with the Aerodynamics group, who provide airfoil shapes to the engineer; the Aeromechanics group, who test for vibration properties; the Heat Transfer group, who test the temperature gradients to ensure that the blade is cooled properly; the Stress and Life Analysis groups, who check the stresses on and wear of the blades and predict how often they would need to be replaced in the field; the Drafting group, who add dimensional information and additional views to the design to prepare the design information for manufacturing; one or more testing groups, who are responsible for completing the necessary engine certification or qualification tests; a performance group, which tests the output of the engine to ensure that specifications are met; and a Manufacturing representative, who ensures that the part can be built for a reasonable cost in a reasonable period of time. Other groups, such as a materials research laboratory, may occasionally be involved.

The engineer responsible for a part must balance the demands of each group, as well as work within his own constraints. The Aerodynamics group prefers thin airfoils for optimal airflow characteristics, while the Aeromechanics group prefers thicker, stiffer blades to reduce vibration. The Heat Transfer group may require cooling channels within the blade, which may conflict with both the Aerodynamics and Aeromechanics groups' goals. Against each of these groups' demands must be balanced the cost and weight of each design alternative. Finally, a design which works well may not be durable, maintainable, or manufacturable, and thus may have to be redesigned, necessitating changes undesirable to any or all groups.

The overall job of the design engineer is one of balancing conflicting requirements. Unfortunately, this is often done by incorporating different perspectives sequentially and iteratively converging on a solution (cf. [6]). Many of the design engineers, when asked to describe their job, used the term "project manager." They describe their job as one of coordinating a group of people who carry out the bulk of the design and analysis work. Most of the design engineers' time is spent coordinating efforts between the different groups.

Design engineers also perform design and analysis work on their own. The analysis performed by the engineers was largely described as "quick and dirty"-analyses to understand the feasibility of new ideas, or to check the accuracy of results generated by other analysis groups. The engineers do perform some design work, which involves generating new design possibilities. This (in most companies) is the smallest part of the design engineers' work.

CAD Systems

CAD technology has been applied in many different ways to design engineering work, and design engineering work was changed in many different ways with the introduction of CAD systems. The divergence in the experience of different companies was due in part to the different types of products being engineered and to variations in the capabilities of different CAD systems. Yet similar systems were sometimes applied to similar tasks in very different ways. Two different groups in the same company doing similar tasks sometimes have significantly different experiences with the same CAD system. One cause of this variance, the design engineers believed, is the variance in managerial attitudes. Managers structure the work for design engineers. They allocate resources to and set deadlines for engineers. They have a large voice in determining how engineering work is carried out. Managers' attitudes about how CAD systems should be applied to engineering work varied widely.

CAD Systems as Electronic Drafting Boards

Some managers saw CAD systems as electronic drafting boards. This is understandable, as many managers gained their engineering experience before CAD systems were developed and may not have had the time to learn the new technology. Managers of this type often view CAD as a drafting board with some additional (and, to them, mysterious) features. They see their subordinates' performance improving on some tasks, but declining on others. Many adopt an attitude similar to that of one manager interviewed: they view the CAD system as a drafting board with a "magic button." For some tasks, the productivity advantages of the CAD system were undeniable. The production of a slightly different version of a previously designed product was accomplished by the CAD system very quickly. But this magic button did not work for other tasks, such as the design of new and complex parts. For tasks such as this, this manager will require that the task be done his way (which often means on the drafting board).

CAD Systems as an Engineering Support Tool

Other managers believed that designing on a CAD system is a process very different than designing on a drafting board, especially if the CAD design is done in three dimensions. Such managers would require that all design engineering be done in three dimensions; they stated that, while designing in three dimensions is a more difficult and more time-consuming process, it provides significant benefits. Designing in three dimensions requires greater mental involvement with the part to be designed- it requires that the entire part be considered simultaneously and completely. Design in two dimensions allows some cheating- some important design details can be ignored and left for a downstream process to determine.

For example, designing the shape of a turbine blade in two dimensions is done by specifying the cross-sectional dimensions of the blade at various points along the blade. During construction of a prototype, a blade is produced by connecting the cross sections with straight lines. The design engineer will then decide how to fill or smooth this prototype to produce the final surface dimensions- a process in which errors can be introduced. When designing in three dimensions, the exact shape of the turbine blade must be specified, which requires a good deal more effort on the part of the design engineer. The result of designing in three dimensions is that (1) the time to produce the first set of engineering drawings is lengthened and (2) the downstream processes (e.g. the production and testing of prototypes) are shortened.

Some managers also stated that the analysis features of the systems allowed for a better simulation and testing of the design before any hardware was built. For example, an engineer in one automobile company built a model of half of an axle and suspension system. He was able to simulate the performance of an actual axle travelling over a rough road. The simulation results corresponded well to test track results. The simulation provided the engineer information about the areas of the axle and suspension that were likely to fail. In the field, the failure of a part, production of a new redesigned part, and retest of the part would take at least six months to complete. The use of a CAD simulation allowed the same cycle to be completed in one to two days. The result was that the design engineer had a better understanding of the design, and a better first prototype was completed. Because of the complexity of the analysis, however, the first prototype was completed behind schedule.

A similar experience was reported in a gas turbine engine manufacturer. To certify an engine for commercial use, the engine must survive the ingestion of birds (as this can occur during flight). The intersection of a simulated bird with a simulated turbine blade was used to test the performance of the engine in this respect. Again, the results of this simulation improved the engineers' understanding of the design and the quality of the first prototype.

CAD Systems and Communication

CAD systems in many companies were used to improve communication. Some engineers, when trying to explain a design concept to others or resolve a design conflict with others, will often coordinate with others in front of a CAD terminal. The rich representation of the design available on the CAD terminal helps ground conversations and minimizes misunderstandings. CAD systems can help create a common language between groups with different backgrounds and jargon. In fact, design engineers will often design in three dimensions, even if designs are still transferred officially on paper to other groups. Design engineers report that a face-to-face conversation with a three-dimensional model as an aid may be the only way to adequately explain the design to others.

Another use of CAD systems as a communication aid was found in a large airframe manufacturer. This company created a "CAD Design Review Room," in which a CAD terminal display was projected onto a large projection-TV screen. When engineering changes to a part were requested or required, all parties involved would meet and review the change, with the engineer in charge of that part using the CAD terminal. The CAD drawing of the part in question was changed, rotated, added to, or simplified by the engineer on the terminal. Thus, all groups saw the design the way they needed to see it. One person's "detail" is another person's "noise," and with the CAD-based design representation all groups could see the design in the manner they preferred.

Engineers will also use the systems to coordinate with others by accessing others' design work directly. Many design errors are simple gaps or interferences between parts. Engineers in some companies could access other parts on their CAD systems and check the fit of those parts with their own. Another example of coordination through CAD systems is the use of standard parts libraries. The Purchasing organization chooses a set of fasteners and purchases them in bulk. The geometry and characteristics of these parts are placed in a CAD library which engineers can access. Thus engineers can easily tell which fasteners are preferable without having to read any releases or call anyone in Purchasing. The coordination between these deparments is thereby made more efficient.

A change that occurred in one surveyed organization was the removal of the group responsible for integrating the different parts of a large project. This group was replaced, in effect, by a CAD file containing the designs for the different parts of the product. The central CAD file was accessible by all and was used by all engineers to ensure that the parts they designed fit with the rest of the project. Each engineer can be responsible for understanding the fit of that engineer's part with the other parts around it, and for resolving any problems that occur.

A similar example was found in an automobile manufacturer. The conceptual design of a new automobile is done through the creation of a clay model. When the conceptual design of the exterior of the new model is complete, the clay model is digitized and this information is sent to the Packaging group (as well as other groups). The Packaging group determines the placement of all components within the automobile. "Envelopes" for each area of the car are created, which define the outlines of the space for the passenger compartment, luggage compartment, engine, transmission, drive train, suspension, gas tank, electrical components, etc.

The Packaging group recently started building full three-dimensional CAD models of all components, and now transfers a CAD file to all groups, defining the envelopes exactly for the groups. With this CAD model, each group now knows exactly where it must place its parts and with which group it must negotiate if more space is needed. The productivity "impact" on the Packaging group is large and negative- it takes much longer to build the full three-dimensional model of all major auto components. The result, however, is a more complete specification of the component envelopes for downstream processes. Managers downstream report that this better definition of the space allocation under the hood leads to less conflict between groups, as fewer misunderstandings occur. This in turn has led to better relationships between groups and greater productivity. Furthermore, this automobile manufacturer believes that the overall development time will be cut significantly.

Concurrent Design

Although concurrent design was not intended as an interview topic, managers interviewed in every company mentioned some effort to implement concurrent design practices. The level of effort is quite different in different companies, however. One airframe manufacturer has radically changed the organizational structure, physical location, and design process to insure that all groups are involved in the design and design engineering process. Other companies, while endorsing concurrent design practices, did little more that encourage engineers to meet more often with engineers in other groups. Four companies had tried implementing a policy that required the design engineer to meet regularly with representatives from other groups, but these efforts were dropped when the meetings were found to be unproductive.

Discussion

Managers in every company surveyed exerted a large influence over the design engineers and their use of CAD systems. Managers' attitudes and knowledge of the capabilities and limitations of CAD systems were a crucial determinant of how effectively the systems were used (cf. [2],[16],[26]). In this section the concepts of physical, human, and social capital will be used to categorize managers' attitudes toward CAD systems.

Managers views of CAD systems can be classified into three categories corresponding to the three types of capital discussed earlier. Some managers saw CAD systems as physical capital, some as supporting and extending human capital, and some as enabling improvements in social capital.

Physical Capital

Some managers saw CAD systems as physical capital, as electronic drafting boards. Managers in this category (such as the manager who saw the CAD system as a drafting board with a "magic button") did realize some productivity gains from the system. The engineers in these deprtments would openly express frustration that much more could be done withthe systems.

Human Capital

Some managers understood that CAD systems could provide the design engineer a better understanding of the design; they saw CAD systems as supporting or extending human capital. Managers in this category believed that CAD systems allow the design engineer to understand the geometry and characteristics of the design more fully. The detailed representation of the design, coupled with sophisticated rendering capabilities, allow the design engineer to understand the design in more detail. Design engineers working at a CAD terminal reach a "resonance" with the design- an ability to understand the design in great detail- that is not as easy to achieve with a drafting board. With CAD systems the design engineer has in front of him a tool that allows him to work with the design as it will appear when it is produced. Engineers report that the tool in effect "disappears," that engineers are able to concentrate on the design and forget about the tool itself. The transparency of the tool enables the design engineer to devote more attention to the design process, and less to the medium of design.

Managers in this category allowed their engineers the time necessary to complete a full three-dimensional model CAD model, as they realized it would improve the engineers' ability to understand the design (and to communicate it to others). These managers would also allow the time necessary to perform detailed analyses of the designs, as they gave the design engineers a better understanding of the characteristics of the design.

Social Capital

The third category of managers saw CAD systems as enabling improvements in social capital. The managers in the previous group, while understanding the capabilities of CAD systems as individual support tools, did not understand the ability of CAD systems to improve communication between individuals in different groups. These managers took advantage of the ability of CAD systems to act as a "common language" between different specialties and (where possible) used CAD design review rooms. They understood that a central CAD file unambiguously communicated design information around a company, enabling improvements such as the removal of the integrating group in the copier company or the improved layout from the automobile Packaging group.

Of the 29 managers interviewed in the ten complex product development processes, 16 viewed CAD systems as physical capital, 6 viewed CAD systems as supporting or extending human capital, and 7 viewed CAD systems as enabling improvements in social capital. This rating is the subjective judgement of the authors, and is based upon the interviews with the managers and their subordinates, as well as the actual use of CAD systems by the managers' subordinates. Managers were not asked to classify themselves.

In every company, there was evidence of different applications of CAD systems. There was always at least one engineer building three-dimensional models, checking the fit of the model with other engineers, analyzing the model with whatever tools were available, and explaining the design to others with the CAD model as an aid. Engineers such as this had to fight management in some companies, but were supported by management in others.

Section 8: Factors Affecting the Use of CAD Systems

There are many organizational policies and actions that affect how CAD systems are used and to which uses the systems can be applied. These policies and actions make possible the use of CAD systems for various activities, and are thus referred to as enablers. These enablers fall into three general categories: *basic* *enablers*, which allow the use of CAD systems as physical capital; *human support enablers*, which allow the systems to support and extend human capital; and *coordination enablers*, which allow improvements in social capital.

Basic Enablers

Good Training: Many training classes (including those offered by most vendors) do very little to teach an engineer how to apply CAD technology to the tasks at hand. More often, these classes provide an introduction to features, but little guidance on how those features should be used. By the time the user has learned how to apply the basic features to his or her own job, the more advanced features have been forgotten. The best CAD training classes require that the engineer bring a design problem from the workplace to class, and complete that task by the end of the class.

Good Support: A good support group will provide assistance to users in learning new features, will keep the system operational, and will respond to users' requests to tailor the system to company-specific tasks. A good support group must be accessible and must respond quickly to requests.

Slow Hardware/Inefficient Software: Many engineers are working on outdated hardware and software. Engineering is a process which requires great mental involvement with the work. Having concentration broken by slow response time can drastically affect productivity. With the cost of machine power falling rapidly and the cost of labor increasing, it is understandable why many companies wait to upgrade their systems. Yet without this, design in three dimensions can be too difficult. Unfortunately, response time is not dependent on machine hardware alone- poor response time can be caused by poorly designed software as well.

Ease of Use and Usefulness: A system that is overly complex in its execution or one that lacks functionality will not allow organizations to gain the full advantage of CAD technology.

Human Support Enablers

Managerial Understanding of CAD Systems: If managers do not understand the capabilities and limitations of their subordinates' systems, they cannot adequately judge their subordinates' behavior. The drafting board provided the manager with instant feedback on subordinates' progress; measuring work progress with CAD systems requires that the manager understand when progress has been made on a CAD model. This is much easier if CAD capabilities are known. Further, managers who understand CAD technology can more accurately gauge the benefits of a proposed new application, and can better guess whether the financial and learning curve costs are justified.

Enforcing Three-dimensional Usage: Engineers sometimes resist designing in three dimensions. The design takes longer to complete and must be thought through more completely; much greater concentration is required in the process. Yet designing in three-dimensions allows other activities to occur:

- Designing in three-dimensions with surfaces or solids provides a manufacturability check. A rule of thumb is: "if it is difficult to design with surface or solid models, it is impossible to manufacture." In addition, it is much easier for an experienced manufacturing engineer to check a three-dimensional model for manufacturability.
- When designing in three-dimensions there is less duplication of effort- all engineers can work from the same model. When designing in two dimensions, the analysis groups must construct their own three-dimensional

models, which may be different from one another. The different groups may also want to see the model from a different angles, or see different information about the model. Only with three-dimensional representation can all groups work from the same model.

- With three-dimensional design, there is a greater ability to explain the design to others, as the design can be rotated and (if surfaces or solids are used) the design can be shaded and hidden lines removed.

Coordination Enablers

Required Use of CAD: One major step that many companies never make is the requirement for CAD use, i.e. the requirement that all parts for new products be created on CAD systems. Often, the learning curve for CAD systems, coupled with strict deadline pressures, will inhibit the use of CAD systems. Those engineers who do not use CAD will impose a cost on those who do and who need to access design information from the non-CAD user.

Moving the Official Design Document onto CAD: When CAD models are used to generate a paper document which becomes the official design document, the urge to make last-minute changes to the paper document only can be quite strong (it may take ten minutes to erase and change the paper, while accessing the file on CAD, changing the model and generating a new drawing can take hours). Yet coordination through the CAD data files is much more difficult if all design information cannot be accessed, or the design information on the system is not current.

One Model: Different groups may need to see the design in different ways. Returning to the turbine blade example, an Aerodynamics group is concerned with airflow lines, while an Aeromechanics group is concerned with cross-sectional surfaces. A strategy which requires that each group construct its own model is much less efficient and more prone to errors than if a single model is translated for all to use, or if the initial model is complete enough for all to access.

Adding Intelligence to the Design: If there exists an organizational norm that the greatest amount of information possible about the design should be placed in the file with the geometry, then the CAD file will provide a richer source of information to those who must access it, and thus make coordination through CAD more effective.

CAD File Naming Conventions: A naming convention for design data files can aid in the location of the design data by engineers, and thus enables coordination by CAD file transfer in some instances.

Standardized Use of Levels: Naming of levels can aid in the use of CAD systems for coordination. Naming levels helps other engineers locate the parts of interest quickly. Further, standards for where design data is placed and where non-geometric information is placed can aid in the understanding of another engineer's work.

Network Transparency: The ability to easily access others' work and bring it into the current work area is important to using CAD systems for coordination. Incompatibility of systems and data files, or technical problems with communication networks can all affect the engineers' ability to work with others' CAD files.

Presence of a CAD Design Review Room: Another characteristic of the implementation of CAD technology that allows improvements in coordination is the presence of a CAD design review room- a room with a CAD terminal connected to a projection-screen television. Such rooms are helpful in using CAD to coordinate work across groups (as discussed earlier).

Conclusions

There are four specific observations that are important to emphasize. First, there are some significant production-related benefits of CAD systems. Even if CAD systems are used solely as electronic drafting boards, some productivity gains will be achieved.

Second, CAD systems, when used as an aid to conversations, create a common language or set of references. This common language allows differentiated and interdependent groups to effectively communicate about design-related issues. The combination of a face-to-face meeting and the availability of a rich and flexible representation of the design lead to a medium of communication that is both unique and powerful.

Third, while CAD systems may be directly responsible for some changes in the way engineering work is done, many changes are only enabled by CAD systems. The manager who believed the initial sales pitches for CAD systems was misled. CAD systems do not necessarily decrease the time it takes for engineers to produce drawings. CAD systems can lead to large improvements in productivity, but only if the work is reorganized to take advantage of the features of the systems. CAD systems' effectiveness as a communication medium allows them to be used as a gateway innovation- an innovation that is important for the other innovations it allows. CAD systems should be evaluated for their ability to enable productive design changes, and not expected to automatically cause changes.

Finally, the most productive changes enabled by CAD systems may entail what appear to be productivity losses at the group level. The use of CAD systems to improve coordination in the early stages of the design engineering process may result in more issues being raised early and more conflicts being resolved early. More work is done earlier, and the result is that it may take longer to complete some initial tasks. Schedules should be adjusted to allow these changes to occur, as the productivity gains downstream (e.g. in the prototype refinement phase) can be significant. It is important that these apparent productivity "losses" be recognized as an "investment," as they may lead to significant downstream gains.

Many companies are experimenting with or have implemented concurrent design methods. Concurrent design practices force the design engineer to work with all other groups when making design decisions. Rather than working with each other group sequentially and iteratively converging on a solution, a concurrent design process will require the design engineer to involve all other groups in all design decisions. The communication demands are thus much greater. Concurrent design has some clear benefits: a wider involvement in the design (1) increases engineers' understanding of other groups' specialties and (2) changes engineers' relationships with other groups. Instead of only seeing a small part of the process, individuals from different groups are invited into the central flow of the product development process. This makes the conflicts that inevitably occur much less tense, and easier to resolve.

CAD systems have the potential to improve the ability to coordinate work within the product development process. If CAD systems are used to communicate design information, concurrent design meetings may become more productive, and the entire process may be more effective. Without the effective communication of design information enabled by CAD systems, concurrent design may be too inefficient to be worthwhile.

CAD systems will not cause any major changes by themselves, but may enable changes that can lead to significant productivity gains. Further, the simple use of CAD systems may not be sufficient to enable some changes- the way in which the systems are used is important. Managers must understand the capabilities and limitations of CAD systems, as well as the nature of the changes the systems enable, if they are to see a full return on their CAD systems investment.

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