Feasibility of Computer-Aided Drafting

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ABSTRACT

Studies made by the New York State Department of Transportation to justify implementation of a computer-aided drafting (CAD) system for structural drafting are described. A demonstration project using existing available equipment during off-shift hours was organized to evaluate operations for this application and provide drawing productivity data. Observations, productivity results, and recommendations for a full-scale drafting operation are presented. The project results were the basis for an analysis to quantify potential cost savings and to recommend a CAD system configuration. The assumptions, methodology, and results of the cost analysis are outlined. The findings led to the conclusion that CAD is well justified from a cost standpoint provided minimum work-load and system utilization requirements are met.

The background studies and investigations made by the New York State Department of Transportation (NYSDOT) for the purpose of implementing computer-aided drafting (CAD) within the department's Structures Division are summarized. The Structures Division is a centralized operation responsible for all bridge design and design management activities for the department. At the time of the study the division was producing in-house contract documents including about 1,800 contract drawings for about 75 bridges a year. The principal activity of the implementation study was a demonstration project that was used to develop a capability in CAD for bridge structures and to provide data for a subsequent cost-benefit analysis.

CAD DEMONSTRATION PROJECT

Organization and Implementation

NYSDOT was in the unique position of having an in-house interactive graphics (IG) system purchased through a federal highway safety grant for the purpose of creating a statewide computer-based map for storing accident information (CLASS Project). As a result of the availability of graphics terminal time during the second and third daily operating shifts, a demonstration project was initiated in the summer of 1981 to evaluate the benefits of computer graphics in the Structures Division. That division investigated CAD by using nine staff members for drafting and engineering support work. Many different types of contract drawings were produced for several bridge projects. The results proved conclusively that computer graphics has not only a place in NYSDOT but a potential for increasing drafting productivity many times over.

The project was staffed with personnel from the division's Structures Design Systems Unit, the Bridge Design Section, and the Preliminary Plans Unit. Planning, scheduling, software development, and project management were the responsibility of the Structures Design Systems Unit. The CAD technicians were volunteers selected from the Bridge Design Section and Preliminary Plans Unit. The plotter operators and system manager were personnel assigned to the department's Computer Services Bureau and the CLASS Project and thus were already involved with the IG system.

Some of the major criteria in selecting the volunteer CAD drafting technicians for this project were as follows:

1. No more than one person would be selected from a single design squad;
2. Personnel selected would do the work assigned to them by their respective design units;
3. All volunteers would have permanent drafting titles, not engineering titles; and
4. All volunteers had to agree to work full time on either the second or third shift.

The project began with a CAD operator-training program for all project members. Each member was given about 3 hr per week of hands-on training from July through September 1981. Each person trained about 30 to 40 hr before becoming proficient enough in the IG system to start productive assignments.

By the end of this initial training period, the CAD technicians were proficient enough to start creating modules (cells) to be used repeatedly for many different drawings. By October 1981 about 60 cells had been stored and were available for use. Cell types include the standard contract drawing sheet with titles, the standard north arrow, and all standard prestressed-concrete shapes. During this time some user-friendly programs were written by Structures Design Systems Unit personnel by using standard software packages available on the IG system. The software development has progressed to the point that to date about 200 cells have been developed and about 25 user-friendly programs are in use.

A major portion of the initial work for this project was convincing some of the design unit supervisors that they would not be losing a skilled drafting technician but gaining a much more productive CAD technician. Most of the skepticism of the design supervisors was due to lack of knowledge of the capabilities of computer drafting, especially not knowing what the final product would look like. Demonstrations of the system and examples of typical computer-produced details were important in convincing design personnel of the merits of computer drafting.

Overall supervision for the structures drafting project was the responsibility of the project managers. In addition one or more persons on each shift were designated as a shift supervisor or assistant shift supervisor. All volunteer computer-drafting technicians were highly enthusiastic and self-motivated, so personnel supervision was minimal. Direct technical supervision was possible only during periods when the CAD shifts overlapped with the prime shift, when the computer-drafting technicians could receive instruction from the project managers or the design unit supervisors for whom they were detailing. A key ingredient in meeting production goals throughout this project was the technical expertise of the drafting technicians. Each was highly experienced and proficient in the detailing practices of the Structures Division and thus needed almost no ongoing technical supervision.

In addition, they were able to learn how to handle computer operations problems with little difficulty, largely because of the assistance provided by the CLASS Project staff.

Project Operations

This project started as a demonstration project but quickly progressed into a production-mode operation for the Structures Division. After a few months of full-time operation, the individual design units could not keep their designated volunteers busy, and the project managers decided to seek work from design squads that had no one involved in the CAD operation. This decision gave the project many more different types of drawings than originally planned. At this time 95 percent of the types of drawings found in a set of contract plans have been produced by the project, including preliminary plans, earthwork drawings, estimate tables, abutment and pier drawings, steel and concrete superstructure framing plans and sections, beam details, and tables.

The scheduling of work was and is important and critical and requires coordination among management, the design engineer, and the CAD technician. To use the equipment most efficiently, enough work has to be available so that each operator has been assigned at least two or three drawings at any one time. By soliciting work from all the design squads in the office, this was accomplished.

The pool concept is the best means of providing a continued, steady work flow to CAD so as to maximize productive use of the equipment. By providing a large pool of possible work, some selectivity can be used in assignments, and this was done during the demonstration project. For example, work scheduling was sometimes concentrated on projects with tight completion schedules. Drawings that could be produced quickly were sometimes emphasized and sought out from as many design squads as possible. Furthermore, the pool concept allowed for some specialization of drawing types among the computer-drafting technicians.

The pool operation also provides a work environment that helps maximize productive use of the equipment. When all CAD technicians are working together, they can freely exchange ideas on operating techniques. To become proficient on an IG terminal, one must find the most efficient of a number of possible ways to perform a given operation. The pool operation provides a means to learn from each other's experiences and greatly speeds the learning process. Having the CAD technican in a separate location also eliminates outside distractions and interference from those not involved with the work. Also, supervision is easier with a pool, because all members are performing similar tasks in a well-defined work space.

To monitor production, a reporting procedure was initiated to allow the CAD technicians to record the time it took them to complete a drawing. This same procedure was also provided for the manual-drafting technicians. As of April 1982, 94 logs of drawings produced on the IG system and 173 logs of drawings done manually were on file.

Observations

Working on a second or third shift and being removed from the design engineers except for an hour or two daily was a major change for the CAD technicians and required some adjustments, mainly by the design engineers. Design computations required quicker checking, and messages as to what details were required had to be clearly stated.

The major communication problem due to shift work occurred between the Preliminary Bridge Plans Unit and their CAD technician. Creation of preliminary bridge plans is somewhat of an iterative graphic design process, requiring a high degree of interaction between the engineer and the detailer. Graphical alternatives of fitting a bridge plan to a site often require immediate review by the supervising engineer. Also, it is difficult to have all the final layout information available from all outside sources before a plan is begun, which means that data are received or revised on an ongoing and sometimes unpredictable basis. For these reasons, continual contact between detailer and engineer is desirable, whether the bridge preliminary is done manually or by computer.

Despite these solely shift-related problems, computer-aided preliminary-plan creation showed great potential. In a fully integrated operation, the bridge site and survey plan would be passed electronically from a highway design file, thus eliminating the need for recreating these data by tracing and digitizing. Layout alternatives can be viewed and modified instantly on a graphics terminal. Finally, certain parts of the preliminary-plan drawings are extremely standardized, which means that they can be produced by using standard graphics cells or application programs much more quickly than by manual means.

Although the IG system was not purchased as a drafting system, it handled this task well. The software was flexible enough to meet drafting needs without difficulty. The programming features that it provided are a tremendously productive asset, and strong programming capabilities should be specified when a new system is acquired. It also had the capacity to handle the large workload of this project with little difficulty.

Problems were encountered only when the drafting operation was running simultaneously with the CLASS data-base system during the second and third shifts. When this happened, which was often, the system would degrade and some long response times for drafting operations would result. At its worst this condition would result in reducing the productive drafting time on a shift by 50 percent. For computer drafting to be fully effective, it must operate on a separate dedicated system free from data-base or other large program operations.

The plotting process was the bottleneck in the demonstration project. The flatbed plotter provided for the CLASS Project was too precise and slow for bridge drafting needs, and the time and effort required for final ink-on-Mylar drawings resulted in a slow turnaround time. There were no delays in submissions because of plotting, but if production increased, delays occurred. Normally a drawing was plotted three times during its production life. The first two plots were ballpoint pen on vellum, the first being an initial-check plot and the second being used for advance detail plans as well as a final check plot. The average ballpoint plots required about 1 hr to complete on the flatbed plotter, which is too long a time for this type of plot.

The final plot, with liquid ink on Mylar, required 1.5 to 2 hr on the average and could not be run unattended. The liquid-ink plotting required constant attention by the plotter operator to minimize variations in line thickness due to dust accumulation on the pens and to watch for skipping of the pen. Also, the pen points used with liquid ink tended to wear out after only three or four plots, so close attention to pen supplies and costs was required. As an alternative, a photographic print was made from a ballpoint plot on high-quality vellum, and it turned out well. The final product is of good, consistent quality and is competitive with ink on Mylar when all costs are compared. It is also a much more reliable way to produce a large number of plots.

This experience has shown that a high-speed plotter of contract-plan size is an essential part of a CAD system. A likely choice would be an electrostatic plotter of sufficient quality for all check and advance plots, and it should be on line to the graphics system. Such plotters are available and they are precise enough to produce final plots if desired; the current flatbed plotter could still be used for final plots only.

From previous experiences cited by other state agencies using CAD, it became apparent that checking of computer-produced drawings is sometimes more precise than needed. Checking appeared to be necessary at the beginning of the project, but the checkers were convinced that the drawings were as good as or better than those drawn with manual methods. It was found that prints from the plotter are faster and easier to check when colors are used to represent different line weights. Although it was not monitored, review time is expected to be reduced substantially as graphics operations increase. Use of repetitive drawings and precise dimensioning eliminates much of the human error.

Results

During the first 6 months of the project, about 84 drawings were produced for 19 bridge projects, including 11 of the 15 to 16 types of drawings found in a typical bridge project document. This number exceeded initial estimates because of the ability of the operators to pick up the technique and the quantity of work available from the design squads.

Uniformity of lines and lettering and accuracy of line position in the drawings could not be faulted. The lettering was made to conform with the Leroy lettering style used in the manual operation. The line weights were selected based on the experience of the drafting technicians working on the project and were set to match line weights for manual drafting as closely as possible.

The productivity ratio determined from the demonstration project data is summarized graphically in Figure 1. Average productivity ratios for each 2-week pay period for the duration of the demonstration project were computed and used to determine the plotted cumulative average productivity. Also plotted is the rolling average for the 10-day pay period, which better indicates the ratios being attained after the initial learning period. Both curves show the learning-curve effect and if extended would eventually converge on a steady-state productivity ratio. The ratio attained at the end of 9 months is shown to be 2.3:1.

It is projected that an overall average productivity ratio between 2.5:1 to 3.0:1 is achievable. The project value of 2.3:1 was attained under conditions that were far from ideal, namely, with an old system that was overtaxed between mapping with data-base and mapping with bridge drafting demands. It was also attained in 9 months of operation at less than full time. Other states, such as Michigan, have documented average productivity ratios for structural drafting of 3:1; 10:1 has been achieved on some types of bridge drawings. Based on this information, a 2.75:1 average ratio is a reasonable and attainable goal and was assumed for a new system implementation.

COST-BENEFIT ANALYSIS

In order to demonstrate the potential cost benefits of implementing a computer-drafting system for the Structures Division, the following cost analysis was made. This study compared the average costs of producing a drawing by manual versus computer-aided methods and was used to determine a CAD system capacity that would best fit production needs and optimize cost savings.

The basic cost and production equations used for this analysis are outlined as follows:

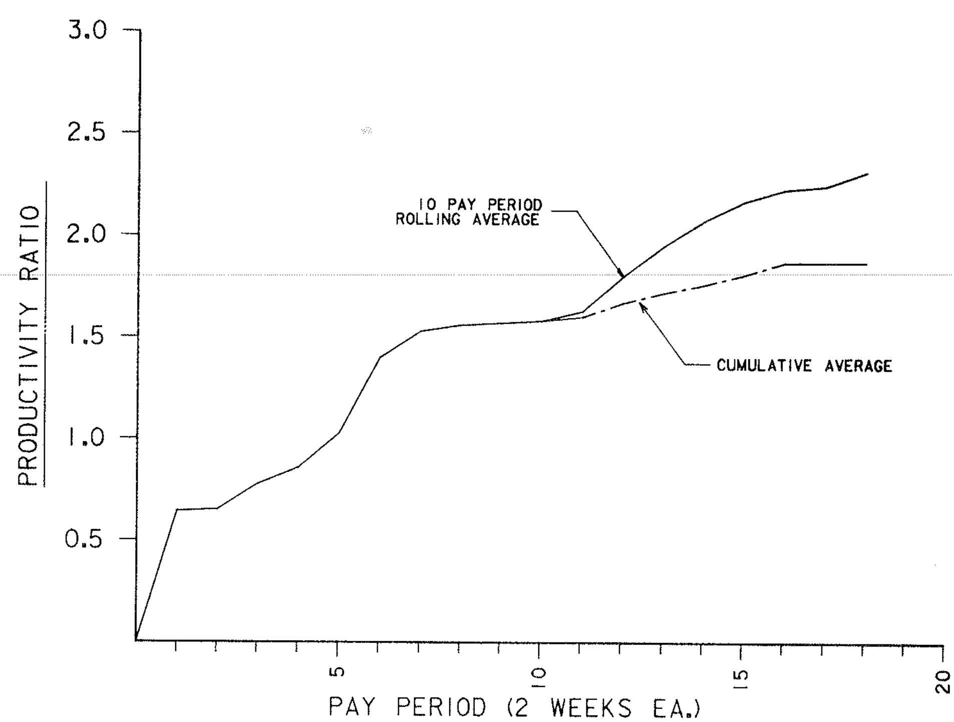

FIGURE 1 Structural drafting productivity in the CAD demonstration project.

Drawing output for computer drafting

$$ND = WYEAR * NT * TUF * (PR/MDR) \quad (1)$$

Manual drafting

$$MDC = MDR * MSCOST \quad (2)$$

Computer drafting

$$GDC = [GSCOST * (MDR/PR)] + (AEQ + ADMIN)/ND \quad (3)$$

where

ND = number of drawings,
MDR = average manual-drafting rate (hours per drawing),
MDC = cost per manual drawing ($/hr),
MSCOST = direct manual-drafting salary cost + fringe benefits ($/hr),
GDC = cost per computer drawing ($/hr),
GSCOST = direct computer-drafting salary cost + fringe benefits ($/hr),
WYEAR = standard work year (hr),
AEQ = annual cost of computer-drafting equipment including maintenance ($),
ADMIN = annual administrative and overhead personnel cost for computer-drafting system ($),
NT = number of work stations (terminals),
TUF = terminal use factor, and
PR = productivity ratio (manual hours per drawing divided by CAD hours per drawing).

The cost equation for computer drafting consists of two parts. The first is the direct cost per drawing of the graphics operator. The second is the cost per drawing of the added expenses of equipment and administrative salaries. These fixed administrative and equipment costs are divided by the number of drawings produced to give their contribution to the cost per drawing. Personnel costs and production rates for manual drafting were determined from department accounting records for a 2-year period and verified by the drawing production monitoring procedure established during the demonstration project. Salary plus fringe benefit costs were included. Equipment costs were based on manufacturer's averages for systems of comparable size. The dollar values used were all present-value (1982) amounts and capital costs of equipment amortized over a 5-year period. The standard work year was assumed to be 2,000 hr per person.

For computer drafting to be cost effective, the PR and TUF must be sufficient to offset the added personnel, equipment, and administrative costs charged to each computer-produced drawing. The PR, or ratio of production time savings per drawing by using graphics over manual methods, directly influences the direct manpower charges. Furthermore, it has an effect on the equipment and administrative costs per drawing, because higher productivity allows for more drawing units to be produced to offset these fixed charges.

TUF measures the amount of time a computer-graphics work station is being used for drawing production and will influence the equipment and overhead charges per drawing. A TUF of 1.0 would mean that the terminal is being used for production for a full 2,000-hr work shift per year. Multiple work shifts can increase TUF to 3.0 (for three 2,000-hr shifts). Full production use per shift is not practical because of equipment down time, operator leave time, and system support tasks requiring terminal use. Based on a combination of employee attendance records, CAD equipment performance records, and information obtained from other agencies using CAD, a 75 percent terminal use per work shift was believed to be reasonable.

Figure 2 shows the necessary combinations of TUF and PR for three IG system configurations that will result in equal CAD manual-drafting costs. Any combination of TUF and PR that falls above these curves will result in a cost-benefit ratio in favor of CAD. This graph indicates that the PRs necessary to make a one-shift operation cost effective are higher than those that can reasonably be expected to be an attainable average for most structural drafting. A one-shift operation could possibly be cost justified if the drawings assigned to computer drafting were limited to those types that demonstrate PRs greater than 4:1, but this would seriously limit the available CAD workload.

Multiple shifts with the terminal use provided will permit achievable PRs as an average for all structural drawings. PRs in the range of 2.5:1 to 3:1 have been shown to be practical, and such values will result in a positive cost-benefit ratio with multiple shifts.

Figure 3 shows CAD costs computed per drawing for various scenarios of number of work stations, work shifts, and PRs. These plotted costs are compared with the average cost of manual drafting. The graph indicates positive benefits of multiple shifts, although increasing from two to three shifts provides less of a decrease in drawing cost than increasing from one to two shifts. Figure 3 also shows the strong influence of the productivity value on cost per drawing for each system and use configuration.

Although maximizing system size and terminal use reduces drawing cost, the configuration chosen must be compatible with the total drawing output of the Structures Division of 1,800 drawings per year. When a target number of drawings for computer drafting is chosen, the following criteria must be considered:

1. The number must be great enough to provide a positive cost-benefit ratio;
2. The number must be well within the 1,800-drawing annual office output to provide a steady flow of work; and
3. The number must provide for a combination of computer drafting plus manual work that is compatible with the entire bridge design engineering work force; if cost savings are to be attained by staff reductions, the number must allow for a manageable rate of attrition to occur while production is being met.

Cumulative costs of drawing production with four-, five-, six-, or eight-terminal systems versus the number of drawings produced are plotted in Figure 4. The cumulative cost of manual drafting is also plotted for comparison. In this graph it is indicated that, in this case, it takes a minimum of about 650 drawings to fully offset the increased costs of computer drafting when compared with manual methods. This minimum is readily attainable from the total division annual workload of 1,800 drawings.

It is also indicated in Figure 4 that system size in terms of number of terminals has little effect on the cumulative drafting cost. The CAD system configuration used for this study was assumed to consist of a series of CAD work stations driven by a central processing unit (CPU), and the cost of one work station compared with the overall cost of the CPU, peripherals, and plotter was found to be small. Therefore the equipment cost approaches a fixed cost regardless of the number of terminals,

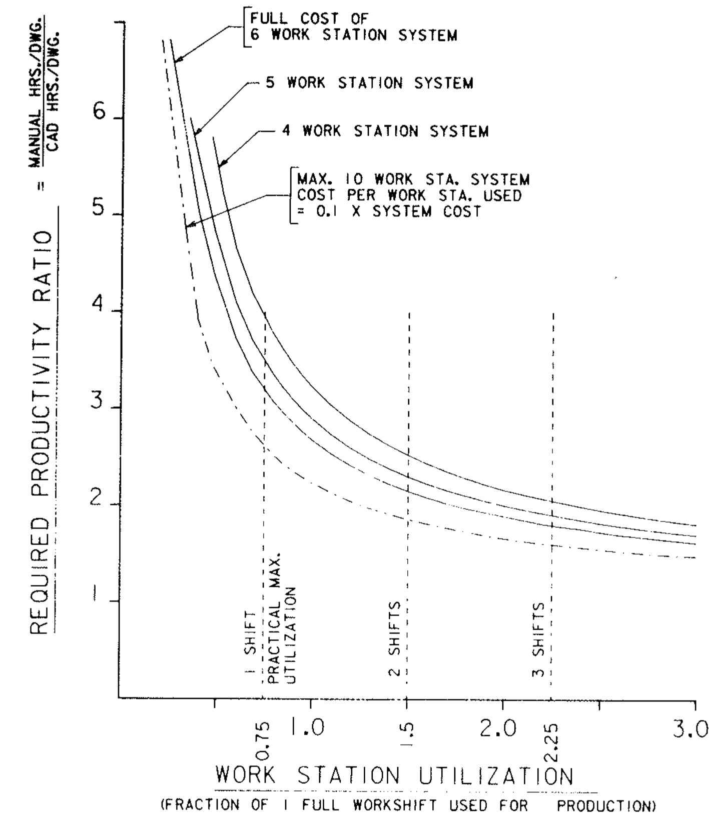

FIGURE 2 Use analysis: equal production cost per drawing for CAD versus manual drafting.

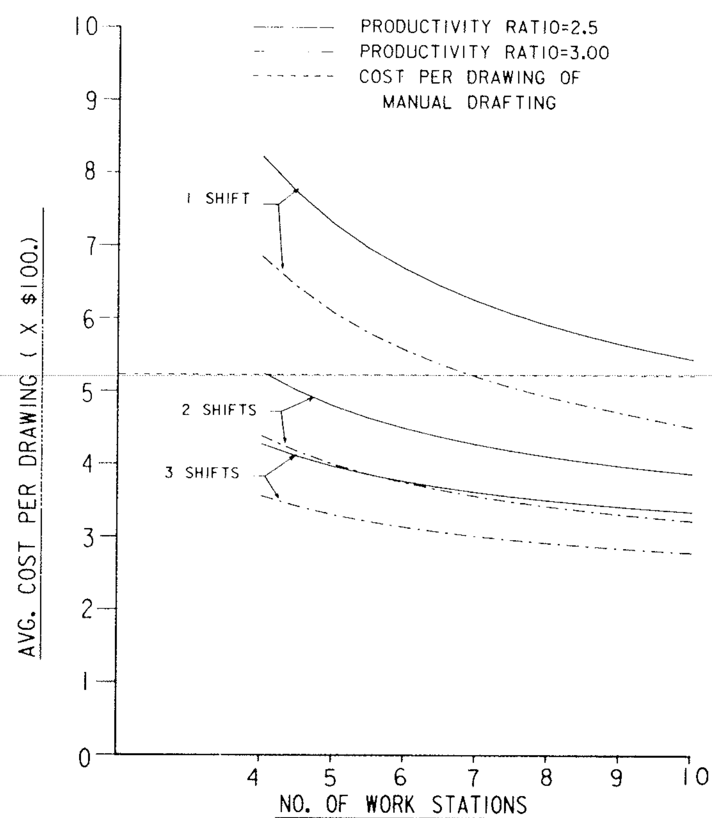

FIGURE 3 Cost per drawing of computer drafting.

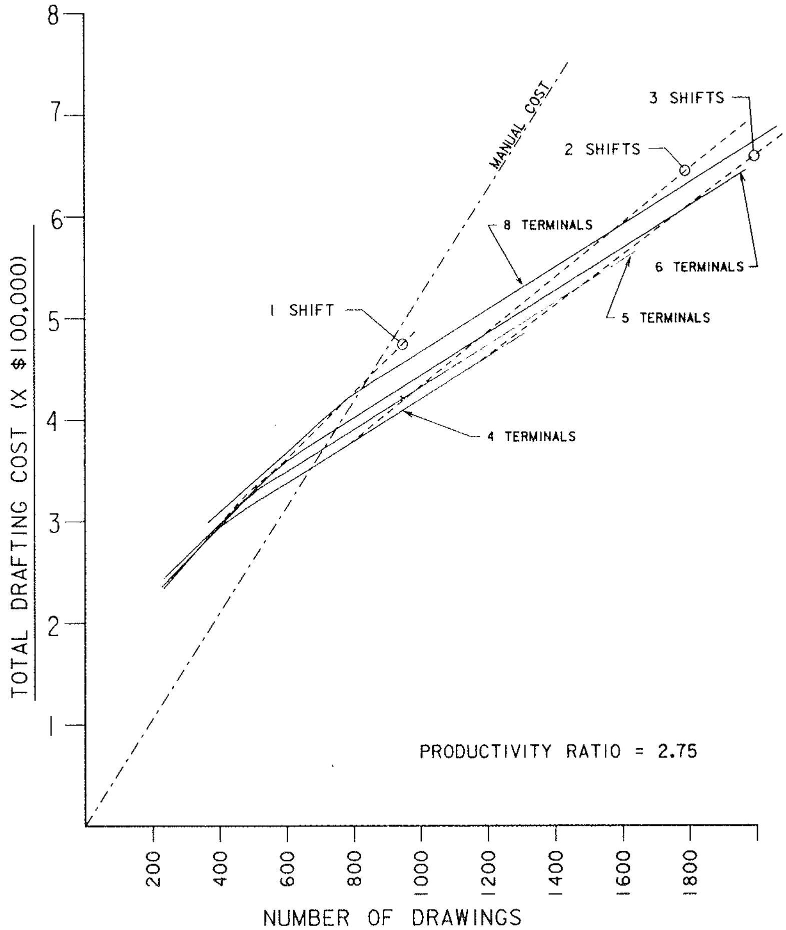

FIGURE 4 Cumulative costs of computer drafting.

and the total computer-drafting cost is nearly a linear function of the numbers of drawings produced. Moreover, cumulative savings over manual drafting increase almost linearly as production increases. Choosing a system for structural drafting becomes a question of deciding on a target number of drawings to be assigned to computer drafting and choosing a system size and terminal use (i.e., number of shifts) that provides the capability for that number.

To implement a full-scale computer-drafting operation for this application, an annual target of about 1,000 drawings was recommended. This is well above the 650-drawing minimum shown necessary for cost effectiveness and will result in a net annual production savings exceeding $100,000. It is also a little more than one-half the total division output of 1,800 drawings, thus providing a larger pool of drawings, which will help smooth the computer-drafting work flow yet allow for some selectivity in drawing types most suited to computer drafting. This distribution of work load also provides for a large enough manual-drafting work load so that a balanced work force can be maintained. In addition to detailing, technicians will be needed for estimating, review work, and other assignments, and they must provide a pool of expertise for vacancies in the computer-drafting work force.

Figure 4 shows that a 1,000-drawing capability is theoretically possible with four terminals on three shifts or five or six terminals on two shifts. It was recommended that a two-shift operation be used to meet this production goal. It was believed that two shifts would be easier to implement initially from a personnel standpoint and allow for more production flexibility than three shifts. A third shift could be implemented at a later date if production demand warranted it or it could be used as an overtime shift. Because two shifts alone are cost effective, any use of a third is cost free from an equipment standpoint. Finally, a five- or six-terminal three-shift operation results in drawing capacity levels too near the available 1,800 limit to be efficient. Four terminals and three shifts fit production needs but allow for no use flexibility or immediate expansion of applications.

The final question was the number of terminals. It was recommended that a six-terminal system be acquired initially. Full production of five terminals on two shifts falls close to the production goal. Adding a sixth terminal provides for nearly a 200-drawing capability increase over five terminals at little added cost and provides a slight excess capacity with full use. Even if the sixth terminal is not fully used for production, its cost is easily carried by the benefits derived from a 1,000-drawing work load. The sixth terminal will provide a little added flexibility for production and development work as well as an equipment backup. Future developmental work is essential to introduce new CAD applications, and this recommended work-shift and equipment proposal will provide the additional terminal time necessary to developmental work in new applications for the department.

Cost Savings

System costs must be justified by providing real dollar savings to the department. These are attained through increased productivity, that is, decreasing the number of man hours to perform a given task (e.g., structural drafting). Increased productivity provides two options for real dollar savings:

1. Savings in personal service costs through decreasing the work force or
2. Savings in expenditures to outside consultants by using the increased capacity to do more work in house.

Whichever option is used to produce savings, it must be assured that a balance in production capacity is maintained between the drafting and engineering phases of the work. Because the CAD system is to improve productivity in drafting only, the total bridge design staffing pattern must be adjusted to balance engineering and drafting needs.

In computing savings in personnel made possible by the CAD system, it was assumed that the current in-house work load of ±1,800 drawings would remain constant. Staff savings will be made by reducing the drafting work force to a level where a combination of CAD plus manual drafting will provide a work capacity equal to that provided by the current fully manual work force. Because CAD would only affect drafting capabilities, the engineering staff would be unaffected. Comparing the reduction in personnel costs with the expenses attributed to CAD resulted in about a $100,000 net savings, as predicted by the cost-benefit analysis.

Although CAD system cost could be justified through staff attrition, larger cost benefits are possible by using the increased production capacity to do more work in house and reduce consultant contracts. In computing the savings in consultant costs that can be attributed to a CAD drafting system, it was assumed that the total CAD plus manual-drafting staff would remain the same size as the current staff, except that some manual-drafting positions would be transferred to the CAD unit. The actual increase in in-house capacity attributable to CAD is then the difference between a CAD plus manual-drafting operation and a fully manual operation with equal numbers of personnel.

To increase overall in-house capability, the added drafting capacity of CAD must be supported by an increased engineering capability. To do this would require adding engineering positions to the design staff. The total cost of this increase in in-house capacity attributed to implementing CAD in this manner is the sum of the CAD equipment plus overhead costs and the cost of the added engineering staff to meet the increase. To determine potential savings, this total cost is compared with the cost of hiring consultants to do the same amount of work. The increased real dollar savings by increasing staff rather than reducing personnel stem largely from the difference in overhead costs between in-house and consultant work. However, it is the addition of a CAD system that provides this capability at the least cost.

Other Benefits

In addition to the cost savings for structural drafting, the CAD system would provide benefits to other applications, both in the Structures Division and in highway design. These added applications would be developed by a CAD applications unit, and as terminal time becomes available through increased drafting productivity, they will be put into production. Major benefits, other than drafting, in structures include the following:

1. Detail checking: Although detail checking can never be eliminated, CAD-produced details will reduce checking and correcting time requirements by producing drawings with fewer errors. This will occur over time as an inventory of standardized details is reused many times, thus eliminating any repetition of errors for these details. This benefit will occur with virtually no added development work necessary.
2. Estimating: CAD software now available for drafting systems can enable the operator to automatically compute areas and volumes of the shapes being detailed. This will eliminate the need for manual computations for these values and reduce the total man hours needed for estimating. Future developments would include integrating a reinforcing-bar list computation and plotting programs with the CAD drafting system, allowing automatic-bar list generations from the CAD-produced details.
3. Standard sheets: Current standard detail drawings now maintained manually by the Structures Division would be stored on CAD files. As specification or policy changes dictate revisions to these details, the modifications can be readily made on the CAD files without the need of manual redrawing.
4. Layout: A CAD system would provide an interactive means to do bridge layouts, eliminating the slow trial-and-error manual methods involving retracing proposed layouts. Future developments in CAD highway design applications will also be applicable to bridge layout. In addition to productivity in terms of time, the CAD operations would produce more accurate layouts than the manual-scaling methods now used.
5. Design: An interactive CAD system would provide the designer with ongoing feedback and opportunities for response and control during an automated design, resulting in faster and more thorough final designs. CAD design systems allow designs to be visualized and provide an efficient means of setting up and producing finite-element or grid models for complex structures and dynamic analyses.

CONCLUSION

Based on the findings of this project, CAD works and can be highly productive in terms of time required to produce an engineering drawing. Key factors enhancing drawing productivity include the use of CAD technicians experienced in the drafting application, a sufficient flow of work, as well as CAD hardware, software, and plotting capabilities geared to the drafting application. The use of a drafting pool provides a better overall production environment but requires careful planning in work scheduling and drawing review.

CAD can also be justified on a cost basis. If the CAD equipment is used sufficiently, the savings from increased productivity can overcome the equipment and support expenses involved. However, the CAD use needed for a significant positive cost-benefit ratio may demand more than a one-work-shift operation. Consideration must be also given to the organizational effects of any increased drafting work capacity due to CAD in a combined design and drafting operation.

For the NYSDOT application evaluated by this study, CAD is cost justified. The required productivity and the minimum cost-effective CAD work load can be provided without significantly affecting the design and drafting production balance. Based on the demonstration project findings and cost evaluation, it is shown that a CAD operation with two work shifts and six work stations will provide at least a net 20 percent savings in the production cost per drawing. Further productivity increases through experience, new applications software, and drawing standardization will increase this net savings.

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