Cost-Benefit Analysis
of Computer Graphics Systems

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
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Ira W. Cotton

Computer Systems Engineering Division
Institute for Computer Sciences and Technology
National Bureau of Standards
Washington, D.C. 20234

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Ira W. Cotton

This report assesses the state-of-the-art in cost-benefit analyses of computer graphics systems and suggests an approach for developing improved methodology. Cost-benefit analyses are distinguished from analyses of system performance in that the latter are directed at optimizing system performance at a given level of investment, while the former are directed at justifying the investment itself.

Computer graphic system design alternatives are first outlined. Then methods of analyzing the performance and costs of computer systems in general and graphic systems in particular are discussed. With this information it is shown how cost-effectiveness analyses may be performed. The next crucial step is to conduct benefit analysis, an ill-defined art. The results of benefit analysis must be combined with cost-effectiveness analysis in order to perform the desired cost-benefit analysis.

An experimental methodology is suggested for better performing benefit analyses of computer graphics systems. A more rigorous formulation of the cost-benefit procedure is then outlined. No attempt is made in this report to actually perform such an analysis.

Key words: Computer graphics, cost-benefit analysis, cost-effectiveness, economics, performance evaluation

1. Introduction

Computer graphics is a sub-discipline within computer science which deals with the manipulation of digital representations of pictorial information, including output of the picture on an appropriate display device and modification of the image in response to operator-initiated

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actions. There are many systems based on this technology in use today, primarily in the area of computer-aided design, and many cost savings are attributed to such systems. Hard evidence to support such claims is mostly lacking, however.

Few studies have been published relating economic principles to the design and implementation of computer graphics systems. Those that have been published deal with only one side of what is essentially a two-faceted problem. Either a detailed analysis of the costs and performance of an optimized system is presented, without corresponding analysis of the economic benefits to be derived; or expected benefits are estimated without discussion of the costs of a system to achieve those savings. The first type of study may be characterized as a cost-effectiveness evaluation; the second as a benefit analysis.

Cost-effectiveness studies are aimed at optimizing the performance of a system according to stated criteria and for a given level of investment. The sensitivity of system performance to changes in level of investment may also be considered within the scope of cost-effectiveness analysis. No value, however, is assigned to the benefits from improved performance. Benefit analysis, on the other hand, investigates just this issue, the value of improved performance, but without regard to the cost of achieving it.

Cost-benefit analysis provides a link between cost-effectiveness analysis and benefit analysis. Cost-benefit analysis is concerned with providing adequate information for making the investment decision. Is the stream of benefits resulting from the use of a system with a given level of performance greater than the required investment? What is the optimal level of investment to maximize net benefit? Such are the questions addressed by cost-benefit analysis.

Cost-effectiveness analysis is necessary but not sufficient for cost-benefit analysis. A valid cost-benefit study requires that the optimal level of performance for a given level of investment be considered. Alternatively stated, for each given level of investment, the value of the benefits considered should be the maximum possible. This is precisely the information provided by cost-effectiveness studies. What cost-effectiveness studies fail to provide is any assessment of the value of the benefits. Such assessments are often difficult to perform, but they are crucial to the investment decision.

We will be concerned in this report with the methodology

of cost-benefit analysis. Methodologies for cost-effectiveness studies will be considered too because, as has just been explained, they are essential for valid cost-benefit studies. The relevant literature will be critically reviewed and suggestions offered where published accounts are lacking. No attempt is made here to actually perform such an analysis.

2. Computer Graphics System Design Alternatives

Before any consideration of economic analysis is possible it is first necessary to outline the technology of the systems under consideration: It is convenient to assign graphic systems to one of three main classes, as follows.

Basic System

Computer graphics systems of the type under analysis consist, in their simplest form, of an analog display device similar to an oscilloscope, a display processing unit which converts digital display commands to analog signals to drive the display, and a general purpose computer system which generated the digital commands in accordance with some application program. This system is illustrated in Figure 1.

Satellite System

This basic system may grow in a number of ways [22]. More and more features may be added to the display processor until it comes to resemble a computer itself. This permits the display device to be located remotely from the main computer, connected by a communications link. Since the link is generally slower than the processing rate of the display, local storage is required to hold the commands sent from the central computer. However, in this type of a system we permit only primary storage; secondary or mass storage such as a disk or drum is not permitted. This type of configuration is called a satellite graphics system because the graphics processor is located at a distance from the central computer but is dependent on it. The general configuration is illustrated in Figure 2.

Such a system offers a number of tradeoffs for the designer [25]. The speed of the communications link, the power of the display processor and the amount of local
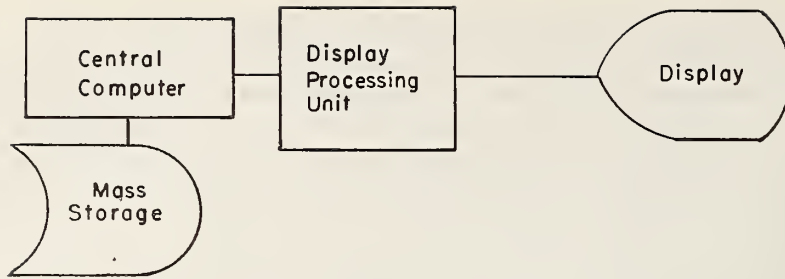
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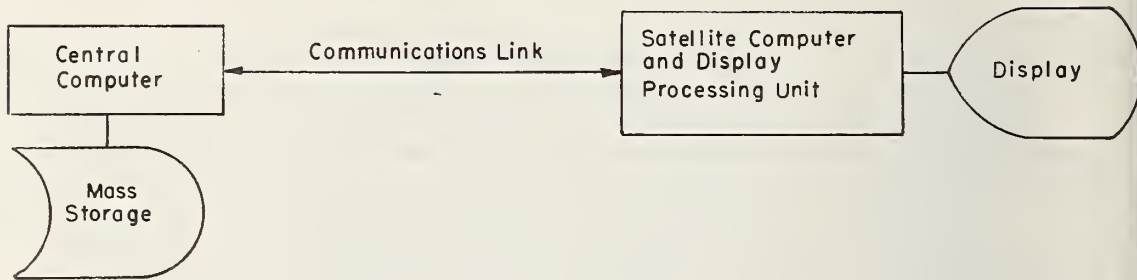Figure 1. Basic Computer Graphics System
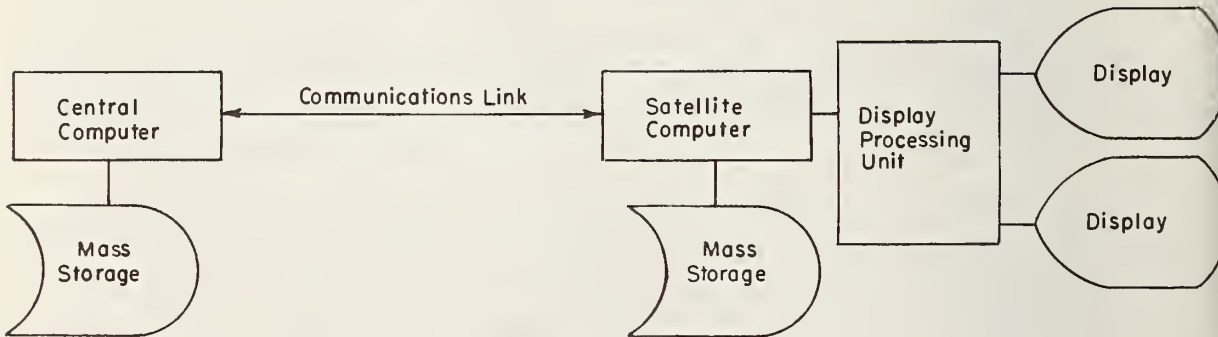
Figure 2. Satellite Computer Graphics System

Figure 3. Network Graphics Configuration

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primary storage all may be increased at increased cost. Also, certain tasks may be performed either in the main computer or in the local processor. The decision as to which components to upgrade and where to perform processing tasks is not obvious.

Network Configuration

The situation can get even more complex. It is well within the capability of today's minicomputers to control multiple displays located remotely from the central computer. In such configurations, it is again desirable to separate the digital processing functions from the analog conversion. In addition, it will probably be necessary at this stage to permit the graphics processor to have a mass storage subsystem. All of this results in a true network configuration where multiple users share facilities at each end of the communications link. This is illustrated in Figure 3.

The attachment of input devices has not been considered in order to simplify the problem. In general, input devices send their data to the closest processor. In the first case this would be the main computer. In the latter two cases input signals would be initially processed by the satellite computer. The degree of processing performed at the satellite in response to inputs, however, is a design variable and may vary widely from system to system [7].

Tradeoffs

For each of these types of systems there are three types of tradeoffs which can be made: hardware/hardware, hardware/software and software/software. Hardware/hardware tradeoffs refer to the possibility of diverting costs from one component to upgrade another. For example, mass storage capacity at a satellite might be reduced in order to pay for a faster data link, or vice versa. Hardware/software tradeoffs refer to the possibility of implementing certain functions either in hardware or software. Character generation is a good example of a function which can be provided either way. Software/software tradeoffs refer to the possibility of performing certain processing tasks either in the main computer or the satellite. Display generation, or the process of formatting display commands from a description of the graphic design in a data structure, is an example of a function which may be performed in either place. All of these types of tradeoffs

challenge the system designer to come up with the optimum
for a particular set of criteria. This is what the art of
system design is all about, and efforts to express these
tradeoffs analytically is what is meant by making system
design into a science.

3. Analysis of System Performance

There are essentially two basic approaches to evaluating
the performance of a computer system: observation and
analysis [30]. The system is either set various tasks
(benchmarks) to perform and is graded on how well it
performs them; or the system is analyzed in terms of
specific parameters in order to derive a measure of
performance. The tradeoff between these two approaches is
between the detail and accuracy of the analysis and the cost
of performing it. The first method has the appeal of direct
measurement: the system is assessed as a whole. However,
benchmarks are expensive to prepare and to run. Parametric
analyses are less expensive to perform, but their results
are less reliable since the effects of small errors in
determining the parameters may be cumulative. Specific
techniques of system analysis fall somewhere on a continuum
between pure observation and pure parametric evaluation.

Feature Analysis

The first serious attempt to provide a formal basis for
comparing computers was a listing of the various
characteristics of different computers published by Adams
Associates. This listing has been called an Adams chart; it
is still published by Keydata and typifies a simple
portrayal of the classical features of computers
manufactured worldwide. In the graphics area, Adams
Associates also published the <Computer Display Review>
which listed the features of graphics equipment; it was
continued by Keydata and is now published by GML
Corporation.

As pointed out in [17], the limitation of the Adams chart
is the inference that performance can be meaningfully
predicted from these classic features. It has been well
established that the use of such raw speed parameters as
clock speed, arithmetic speed, memory speed, word size or
I/O rate can be misleading in predicting comparative
performance between different systems. Over the years, many
people have taken different combinations of these classic

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features and have used these combinations as figures of merit to infer performance measures.

Any listing of simple features fails to incorporate the differences that each system designer included to improve his system. The power of each instruction set combined with each system's architecture is not indicated; the effectiveness of system software is not considered; and factors for evaluating special capabilities such as multiprogramming or multiprocessing are lacking.

Instruction Mixes

A major advance over the feature analysis approaches was the development by the Auerbach Corporation of a standard set of small problems which could be programmed by experts for the variety of different machines and configurations under consideration. The results yielded the amount of memory required, the amount of code and similar detail. The implication is that performance on these standard problems is indicative of the performance on actual user problems, and that small-problem performance is indicative of large-problem performance.

As Johnson observes, however, all instruction mixes [17] suffer from the limitations that the actual mix in use may or may not correspond to that of the "standard" mix. Further, none of the instruction mixes yet devised provide a reliable indication of full load behavior of computing systems. This is an especially serious shortcoming when attempting to predict the performance of multiprogramming or multiprocessing systems. The full load performance of such systems does not appear to be proportional to its small-problem performance. Nevertheless, simple instruction mixes have been widely used over the years because they are simple, easy to use, and provide a reproducible evaluation methodology.

The application of this technique to the analysis of graphic systems is reflected in the set of test patterns which was developed by Adams Associated for their <Computer Display Review>. These patterns were designed to be coded for each display system to be evaluated. One immediate result would be a comparison of the number of words necessary to code the pattern in its entirety. The results of running each pattern were the percentage of the pattern that could be displayed flicker free - a measure of the capacity of the display for applications of which the test

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patterns were supposedly representative. The patterns used
were the following:

Alphanumeric Test Pattern - The alphanumeric test
pattern is representative of applications requiring the
display of tabular or free-form character data. Figure 4
illustrates this test pattern.

Weather Map Test Pattern - The weather map test
pattern is representative of a class of applications
including geographical or mathematical contour mapping as
well as sheet metal styling. Figure 5 illustrates this
test pattern.

Graph Test Pattern - Graphs and charts are very common
displays, both in business and scientific applications.
Figure 6 illustrates this test pattern.

Architectural Drawing Test Pattern - The architectural
drawing test pattern is representative of applications
where a large quantity of unstructured data must be
displayed with high precision. Such applications include
circuit board layout and mechanical design. Figure 7
illustrates this test pattern.

Electronic Schematic Test Pattern - The electronic
schematic test pattern is representative of applications
where pictures are constructed hierarchically, using
repeated instances of certain patterns or subpictures.
Such applications include logical design and certain
layout problems and mechanical analysis systems. Figure
8 illustrates this test pattern.

Kernels

A more sophisticated version of the instruction mix
approach to the anlysis of system performance uses
"kernels." A kernel is a complete nucleus problem;
meaningful kernel problems are selected according to the
type of application of interest, e.g., a matrix inversion
for scientific problems or a small sort for business
applications. The execution time of a set of such problems
is assumed indicative of the system's execution of the whole
application. When kernels are programmed by experts on
their respective machines and the actual software of that
system is used, the results can be good indicators of that
small-problem behavior of that system.

System Valves		System Status	System Signals	
SUPERHEATER	C	*TRIPPED*	STEAM PRESSURE	N
REHEATER	C		FURNACE PRESSURE	N
MAIN GAS SHUTOFF	O		GAS TEMPERATURE	N
VENT	O		COMBUSTION ·	M
MAIN OIL SHUTOFF	C		FORCED DRAFT FAN	R
RETURN	C		AIR HEATER	O
NORTH	C			
SOUTH	C		IGNITOR CHARGED	Y
			GAS READY	Y
IGNITOR SHUTOFF	O			
VENT	C		OIL READY	N
			DUAL PERMISSIVE	N
PENTHOUSE NO. 1	O			
NO. 2	O		MODE SWITCH	C
VENT	O		PURGE REQUIRED	Y

BURNERS

	1	2	3	4	5	6	7	8	9	10
STATUS	-	-	S	*	*	*	I	-	-	-
IGNITOR										
FLAME	-	-	-	-	-	-	-	-	-	-
TRANS	-	-	-	-	-	-	-	-	-	-
SHUTOFF	C	C	C	C	C	C	C	C	C	C
MAIN FLAME	-	-	N	F	F	F	-	-	-	-
GAS SHUTOFF	C	C	O	O	O	O	C	C	C	C
OIL SHUTOFF	C	C	C	C	C	C	C	C	C	C
UNIT	O	O	O	O	O	O	O	O	O	O
ATOM	I	I	I	I	I	I	I	I	I	I
PURGE	C	C	C	C	C	C	C	C	C	C
COOL	C	C	C	C	C	C	C	C	C	C
DAMPER	O	O	O	O	O	O	O	O	O	O
CONTROL										
IGNITOR	-	-	-	-	-	-	-	-	-	-
GAS	-	-	X	X	X	X	X	-	-	-
OIL	-	-	-	-	-	-	-	-	-	-
DUAL	-	-	-	-	-	-	-	-	-	-
OFF	X	X	-	-	*	-	-	X	X	X

Figure 4

ALPHANUMERIC DISPLAY TEST PATTERN
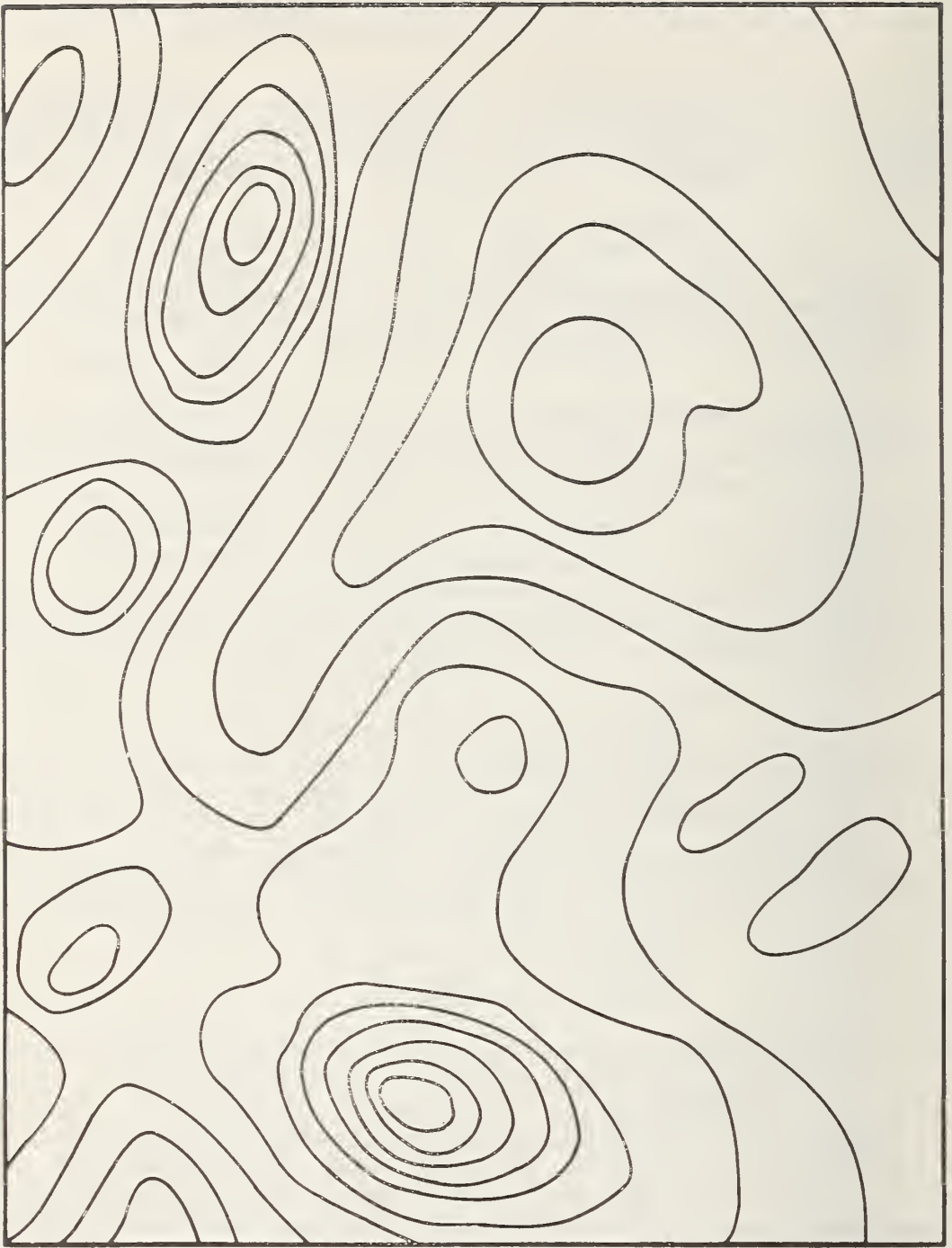
Figure 5

WEATHER MAP TEST PATTERN

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DISPLAY UNITS SALES
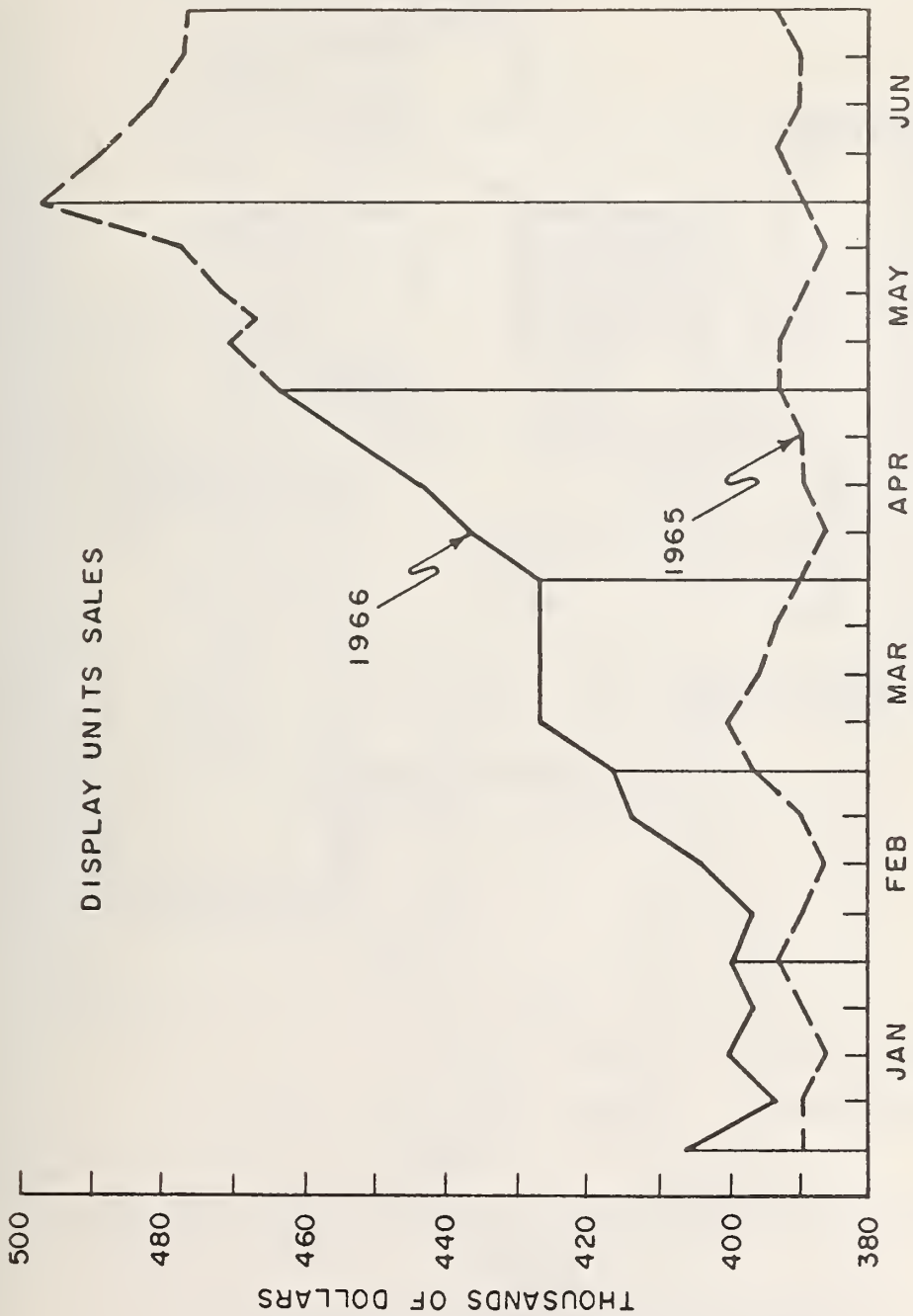
Figure 6

GRAPH TEST PATTERN

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BOILER
4'0" X 5'6"
22 SQ FT

FUEL
4'0" X 5'2"
2I SQ FT

LAUNDRY
3'8"X5'6"
20 SQ FT

W.C.
3'8"X5'6"
20 SQ FT

KITCHEN
102 SQ FT

BATHROOM
42 SQ FT

CUPBOARD
1'8"X 3'2"
5 SQ FT

PASSAGE
154 SQ FT

HALL
35 SQ FT

BATHROOM
3'0"X5'0"
15 SQ FT

DINING ROOM
9'0"X 9'6"
85 SQ FT

LIVING ROOM
13'6" X 15'6"
209 SQ FT

BEDROOM
10'0"X 14'6"
145 SQ FT

N

TOTAL FLOOR AREA   875 SQ FT

CIRCULATION   189 SQ FT   22 %
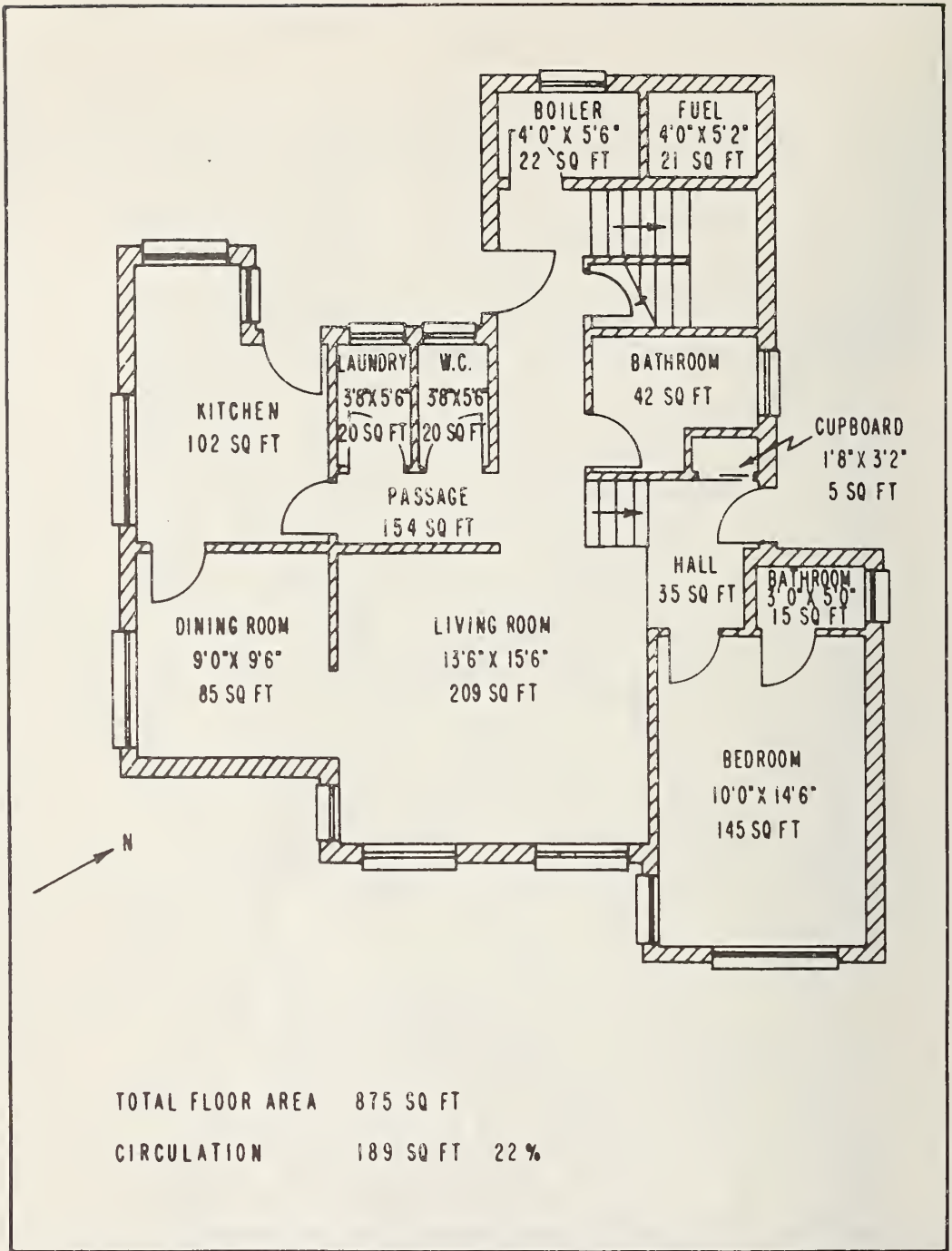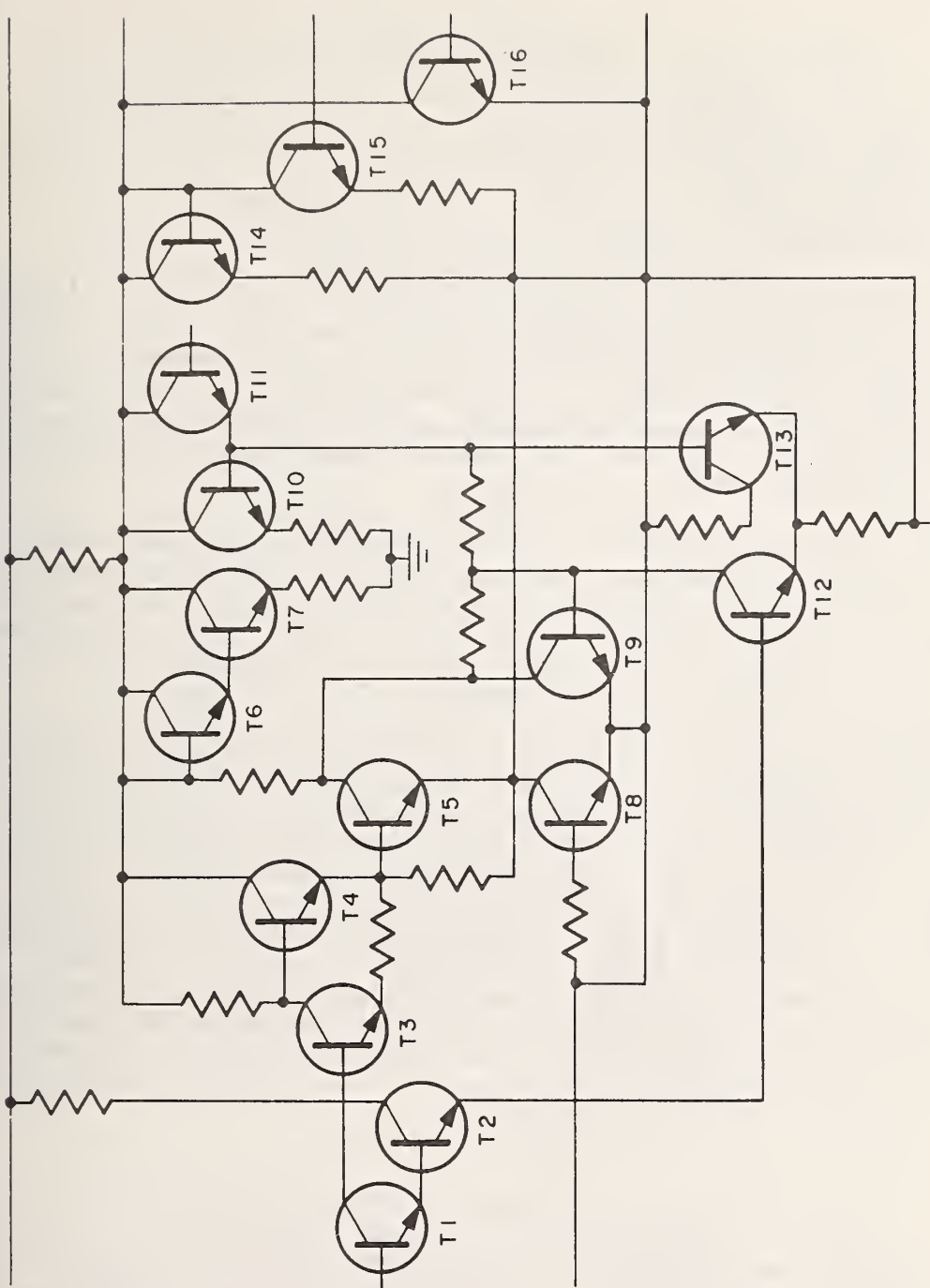
Figure 7

ARCHITECTURAL DRAWING TEST PATTERN

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Figure 8

ELECTRONIC SCHEMATIC TEST PATTERN

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Benchmarks

The most reliable and accurate measurement technique that has been developed to analyze total system performance is to actually code and run a representative mix of complete programs selected from those that are to be run in the actual application. Such sample programs are called "benchmarks." However, pitfalls still exist: the benchmark programs run in sequence may not accurately represent the nature of the work to be performed. Combining several benchmarks partially alleviates this problem, but choosing the right combination of benchmarks is also difficult. Still, as long as benchmarks are run in the large and small mixes expected in the actual operation, a good indication can be obtained of both the large and small problem behavior of the system.

The real limitations of the benchmark approach are that it takes a large effort to develop the sample programs and to prepare realistic data. The task is difficult enough for batch-oriented computer systems for which some libraries of programs written in standard compiler languages have been developed for benchmark purposes. It is nearly an impossible task for computer graphics systems where the programming systems for each are completely different. Also, the results of running benchmarks are only as valid as the benchmarks are representative of the real application mix. Graphics programs typically are composed of a number of different modules with radically different characteristics. Furthermore, an essential part of the graphics programs are the sequences of operator inputs which direct the execution paths of such programs. These sequences are difficult to model and expensive to actually generate in a test situation.* Thus, developing benchmarks for graphics systems which are truly representative of actual applications is difficult to do and the benchmarks are equally difficult to run.

Simulation

A final technique which can be used used in performance analysis is simulation. Simulation cuts across the two general approaches of observation and analysis. To use this technique, a model is constructed of the system under consideration and the performance of this model is "observed" under the desired conditions. The model

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* Work is in progress by a number of researchers at The Mitre Corporation and at the National Bureau of Standards on "Terminal Environment Simulators" which can serve as drivers for benchmark programs for interactive systems.

represents a simplification of the actual system which is
constructed from analysis of the system. If the model
accurately represents all the salient features of the
actual, when it is run with the desired (simulated) workload
the result is analogous to observing the actual system.

Of course, the results of simulation can be no better
than the many assumptions that go into the construction of
the model and into the design of the simulator.
Constructing a computer system simulator for performance
evaluation purposes is, as has been pointed out,[4] not an
easy task. If the level of simulation is too fine, the
simulator will be too costly to use. If the level is too
gross, not enough information will be yielded. Despite
these difficulties, simulation is becoming much more widely
used, and a good simulator properly used may be one of the
better tools for predicting system performance accurately.
As we shall see presently, it is also a technique which can
and has been used to analyze computer graphics systems.

4. Cost Analysis

The principal problem of the cost analysis of computer
systems is to express all the costs of alternative system
proposals in a form suitable for analysis. This requires
that ALL relevant costs be included, and that all costs be
expressed in a comparable form. The question of which costs
to include has been well treated in the literature. Joslin
[18] presents a detailed analysis of all the types of costs
which must be included in evaluating a system design
alternative. The main complication in many cases is the
need to include development costs in the analysis which are
not known in advance but which must be estimated.

Cost Estimates

If two or more proposed systems are to be compared, it is
necessary to compare the amount of development effort
required for each. Data for such an analysis is "softer"
than data describing the pricing of components or even
charges for the use of components. Substantial work has
been done in developing formal techniques for estimating
such costs [20, 24], but their main effect has been to
reduce the margin of error from outrageous to large. Yet
the estimates made of the cost to implement functions in
either the central site or the satellite may be the dominant
factor in system selection.

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For example, large systems today all come with operating systems, and most with communications handlers as well. On the other hand, few minicomputers come with the type of operating systems which would be required to shift some functions from the central site to the satellite. The cost to implement such an operating system may be critical to determining the cost-effectiveness of the proposed division of labor.

Of course, given a large enough number of satellite systems over which to share the total development costs, the average development cost may be made arbitrarily low. Thus, an honest and realistic assessment of the expected number of replications must also be made. This is primarily a market research problem.

Comparable Form

The other problem of cost analysis is to express all costs in comparable forms. The assignment of the appropriate unit costs to the use of the various resources is of critical importance. A controversy may arise in the analysis of graphic systems over whether to price at average or incremental costs. For resources which would not be present if there were no graphics system, incremental and average costs are the same. However, if existing facilities are used part time for graphics, the incremental costs will be less than the average costs. If any tradeoff is to be valid, costs for resources in the central system and at the satellite must be comparable. This can be accomplished by using, in all cases, equivalent monthly rental charges or average resource utilization charges, as appropriate.*

For example, a graphics processor cannot be utilized at no cost simply because it is owned and always available. An equivalent monthly rental charge must be determined and used to derive unit-time operating charges so that they may be aggregated with the charges for the central processor, which are likely in this form already. Likewise, file storage charges for devices at either location must be represented in equivalent, non-zero terms.

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* Actually, the costs used for the analysis may vary according to the purpose of the analysis. An individual company considering adding a graphics capability to an existing facility will want to use incremental costs in order to determine if the addition is warranted. An analyst wishing to compare two alternative graphics systems in the abstract would prefer to use a measure which assigns a cost to resources irrespective of the use to which they are put.

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Fixed and Variable Costs

The concept of fixed versus variable costs is also a relevant one. Development costs such as design and programming costs are fixed, as are hardware components in the graphics terminal since they cannot be used for any other purpose (their cost is fixed regardless of utilization rate). In contrast, the use of central site resources such as storage and the execution of programs are variable costs, since the central computer is shared by a large number of users who only pay for the units of each resource as they are used. The costs for some resources may be either fixed or variable depending on the particular arrangements. For example, communications charges would be fixed if a leased line were used and variable if dial-up facilities were used.

The significance of expressing the charges in this manner is that where fixed charges dominate, total costs are relatively constant but the unit operating costs for a given configuration are very sensitive to the level of usage. In such situations, only high utilization of the graphic equipment can bring down the unit cost [26]. The sensitivity of unit costs to level of usage may be reduced if fixed costs can be converted to variable costs. For example, a higher speed communication link may make it possible to store programs and data at the central computer which are used by the graphics program at the satellite. This would permit the amount of memory at the satellite, which represents a fixed cost, to be reduced in favor of use of storage at the central site, which usually represents a variable cost.

However, the argument goes two ways. Above a certain level of utilization, called the "breakeven point", it is more economical to convert variable expenses to fixed ones. Communications charges are an excellent example -- above a certain level of utilization it is cheaper to lease a full time link than to make a call each time. So estimates of the level of utilization for a system may still be critical to system design decisions.

Generally, the problems of cost analysis for computer systems are well-understood (though they may not be well-solved). Computer graphics systems are not so unique in this regard that they present any special problems. Perhaps the greatest challenge for cost analysis is to obtain results in a form such that the marginal costs of performance were obvious or could be easily determined. This would permit the costs for improved performance or the

savings from reduced performance to be more easily used in
making design decisions. A parametric formulation
explicitly relating costs to level of performance and
utilization rates could serve as input to a decision model.

5. Cost-Effectiveness

Cost-effectiveness analysis is a technique used to
compare alternative systems where the benefits to be derived
cannot be determined quantitatively. The object of
cost-effectiveness analysis is to select either the system
with lowest cost for a given level of performance or
greatest performance for a given level of cost. The method
requires that either the costs or the performance associated
with all the systems under consideration be equal. If both
costs and performance are different for any two systems to
be analyzed, then cost-effectiveness analysis is impossible
since the parameters have different dimensions and may not
be compared.

The application of cost-effectiveness analysis is fairly
straightforward. First it must be decided which parameter
to hold constant -- cost or performance. Cost is frequently
held constant when there is no absolute level of performance
which is required. In this case, a fixed amount of money is
made available and the analysis seeks the system with which
offers the greatest performance. A measurement criteria is
selected and the systems are evaluated according to that
measure. The system which measures the greatest --for
identical cost-- is the most cost-effective. Tradeoffs
between system components may be investigated by varying the
mix of components subject to the constraint that total
system cost remain the same.

The alternative approach is to specify in advance the
performance required of the system. The system is selected
which offers at least that level of performance for the
least cost. Performance in excess of the specified
capabilities is ignored in the analysis. For such systems,
tradeoffs focus on the reduction of performance (and with
it, cost) to the point where performance just equals that
required.

Many studies have been published discussing the tradeoffs
involved in the design of graphics systems [16, 22, 25, 31,
32]. However, few published results show any serious
attempt to quantify these tradeoffs. Quantification is
necessary if a true cost-effectiveness analysis is to be

performed. One of the first published results of a quantitative analysis of design tradeoffs was Foley's study of satellite graphics systems [11].

Foley's Analysis

Foley defined optimum design of a computer graphics system as "maximizing a display system's performance subject to a cost constraint." In his view, optimum display design can be thought of as a resource allocation problem. The resources are dollars which can be allocated to the purchase of display subsystems of differing individual performance. System response time was employed as the sole measure of system performance. (Minimizing response time means maximizing performance). Total system performance is determined from a model of how the subsystems fit together. The parameters of the model are functions of the capabilities of the graphic hardware and of the computational requirements of the graphics application. The model can be analyzed using numerical queueing analysis or simulation to obtain an average response time prediction. By applying an optimization procedure, the "best" graphics system configuration, subject to a cost constraint, may be found for several applications. The optimum configurations are in turn used to find general system design guidelines.

Foley used a combination of kernels and instruction mix techniques to evaluate the computer power of the remote display controller. Basically a set of "display commands" was defined. These commands are at a level higher than machine instructions but lower than a high level language. The commands are coded in the machine language of the controller and timed. Each display command timing is weighted by a factor representative of the relative frequency of execution of that command for a particular application. The greater the value of the weighted instruction execution rate (the reciprocal of the command execution timing) the better suited is the corresponding controller for the application. The full account of Foley's research [10] indicates that he also employed the Adams' test patterns in a similar manner to compare the suitability of display controllers for different applications.

Foley's analyses yielded curves of the form shown in Figure 9. Such curves show the price which must be paid for a given level of responsiveness. Performance is actually the reciprocal of response time, so that figure 9 illustrates the relation between performance (output) and cost (input). The decreasing slope of the curve reflects
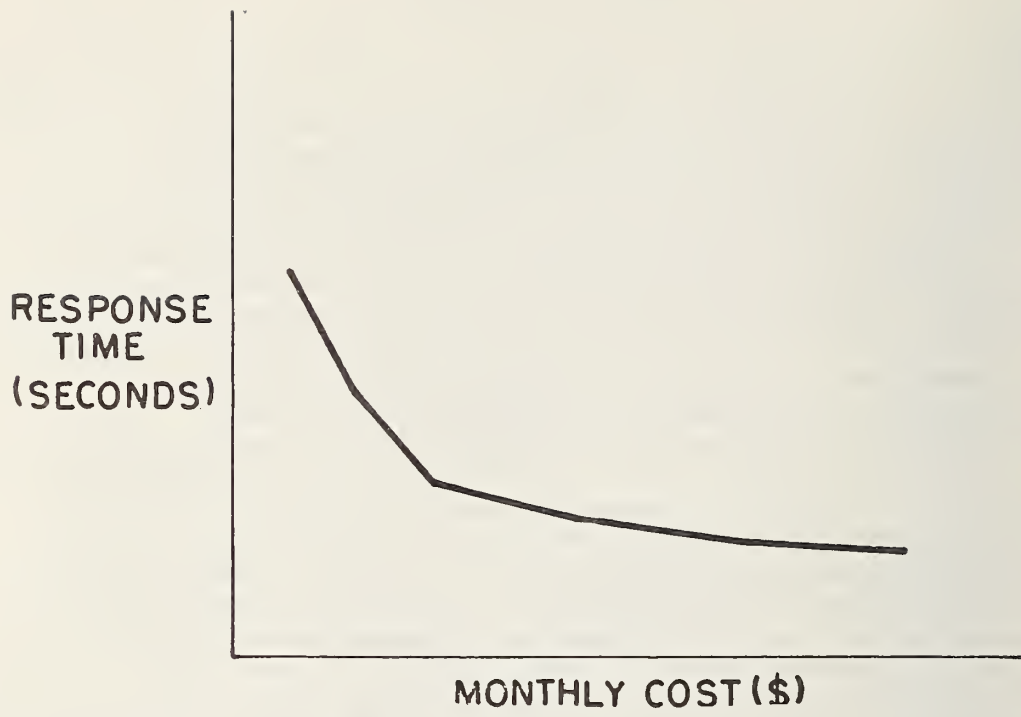
Figure 9. Typical Result of Foley's Analysis

the decreasing marginal productivity of additional units of cost in improving performance. The analyses also revealed that different regions on the curve were associated with the upgrading of different components in the system. Simply stated, this means that different components were being upgraded when performance was improving most rapidly than when performance was increasing less rapidly. Thus the analysis yielded a set of decision rules indicating the order in which a limited amount of additional money should be spent.

Cislo's Approach: Simulation

Cislo expanded on Foley's approach by considering a more complex model of a graphics system in greater detail [6]. Foley neglected the cost of resources at the central computer; Cislo's study includes them. Cislo also modeled a multiterminal system in which each terminal is used for a different application; this went beyond Foley's analysis. Finally, Cislo employed simulation in contrast to Foley's use of queueing analysis.

Cislo's model of a graphic system decomposed the operation of the system into a number of low level operations which might be viewed as the kernel problems of a display system. The activities included in the model are listed in Table 1; Figure 10 illustrates the model itself. A GPSS program based on the model was written and used to exercise it. The program simulated operation of the system by generating transactions which correspond to user requests. The interarrival time between requests was determined randomly from a negative exponential distribution. Similarly, the selection of the appropriate routines to process the request was determined stochastically.
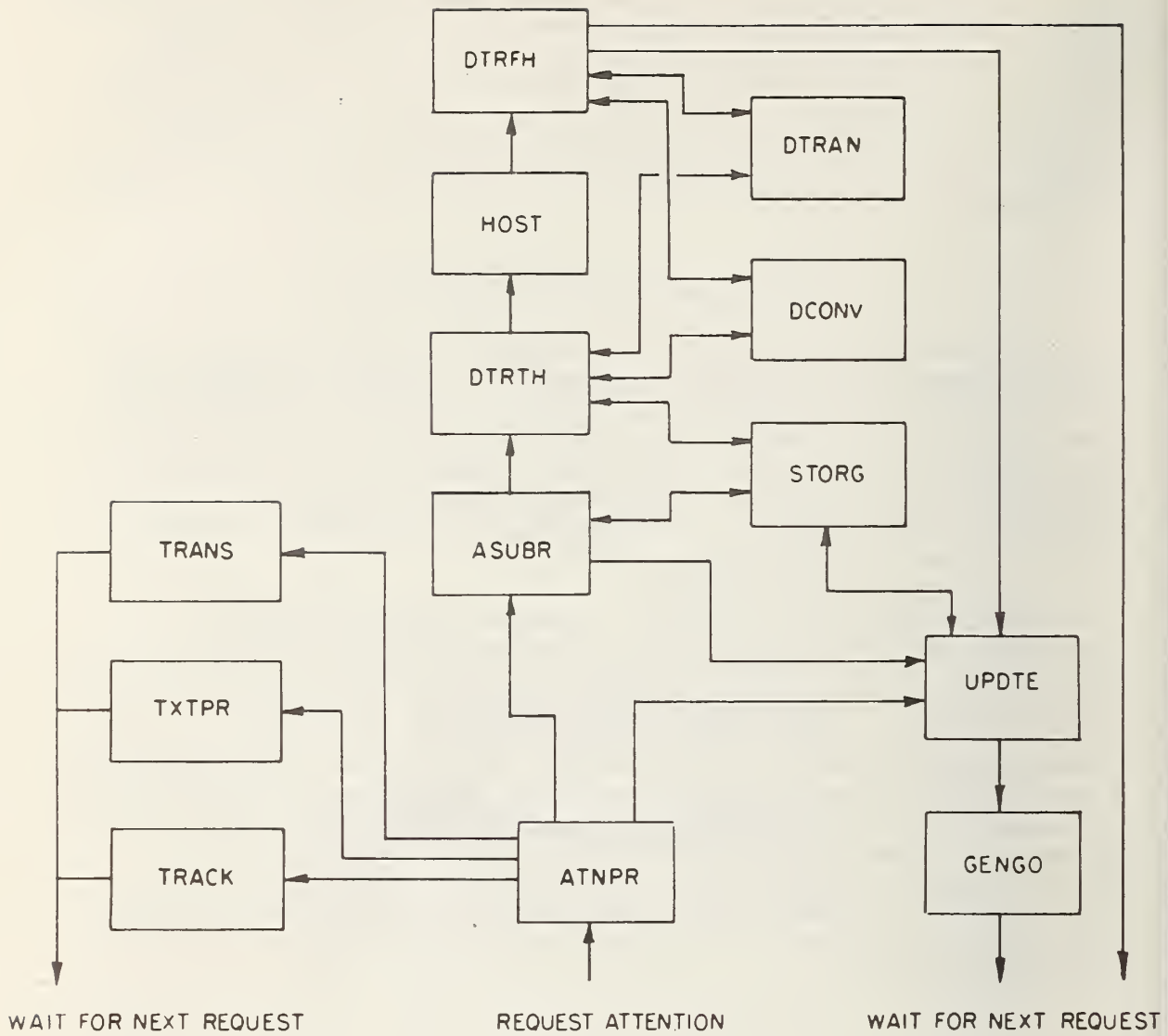
21

Figure 10. Cislo's Graphic System Model

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Activity	Mnemonic
Attention Processing	ATNPR
Transformation	TRANS
Text Processing	TXTPR
Tracking	TRACK
Application Processing	ASUBR
Data Transmission to Host	DTRTH
Host Computer Processing	HOST
Data Transmission from Host	DTRFH
Data Conversion	DCONV
Secondary Storage Operation	STORG
Update Data Structure	UPDTE
Graphic Order Generation	GENGO

Table 1. Model Activities

The parameters of the model are very similar to those of Foley's model and the data were similarly obtained. Published data were used for simple parameters such as instruction execution and data transmission rates, and simple test programs were generated for the estimation of such parameters as the time required to generate graphic orders. Application-dependent parameters such as the probability of generating a given number of graphic orders were much more difficult to estimate, and in many cases were simply assumed.

In exercising the model, it was decided to hold these latter parameters constant while varying the hardware parameters. Accordingly, the operation of eight different hardware configurations, involving changes to the main CPU, display CPU and data transmission facility, was simulated. The results were in accordance with Foley's findings, but the method accorded much more detailed descriptions of system activity. The expanded version of the model which would handle multiple independent graphics consoles was described but not implemented.

Validity of Indicators

These techniques which have just been described offer much hope of permitting the analysis of computer graphics to be performed on a much more systematic and quantitative basis. The value of the analysis, however, is dependent on the validity of the variable(s) which is optimized as an indicator of total system performance. Accordingly, this

discussion of cost-effectiveness is concluded with a discussion of this question.

Response Time

The response time provided to a user has long been considered a critical parameter in the performance of interactive systems. The general approach of system designers to this parameter has either been to "minimize it", subject to available monetary resources, or to insist on a minimum response time, e.g., 2 second response 95% of the time, regardless of the cost. This approach is overly simplistic and may be far from cost-effective for a number of reasons.

First of all, not all interactive tasks require the same responsiveness of the computer. Miller [23] has shown that there are several classes of interactive activity with quite different response requirements. One class is the input of data by various means. An immediate response of no longer than .1 - .2 seconds is required for this class to signify acceptance of the data. A second class is characterized by a user engaged in high-intensity "brainstorming" requiring the ready access of data from his own "short-term memory." Such activity requires no longer than a two-second response in order that the chain of thought not be broken. A final class includes those activities which complete a subjective (sub)task or (sub)purpose. More extended delays (up to 15 seconds or more) may be permitted following such an activity completion, or "closure", than in the process of obtaining a closure.

These findings may have an important impact on system design, since alternative methods exist to provide each type of response. For example, verification feedback and simple data manipulations may be supported on a so-called "intelligent terminal" with its own local mini-computer. Since the response from complex application-dependent computations may be permitted to be less rapid, these may be provided by a large time-shared computer, possibly located at some remote location and connected by a communications circuit. A cost-effective design will assign the function of providing each type of response to the facility which can meet the required response and meet it at least cost.

Other factors may also be considered relating to response time. A uniform response time has come to be recognized as very important (in contrast to a response time which varies widely from transaction to transaction) -- so much so that

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in some applications the responsiveness of the system is artificially delayed when it falls below the desired value, so that the variability of response is thereby reduced (at the expense of lower average response time).

Finally, some experimentation has been performed into the effects of restricting the free access to the computer after it has responded to each major request (similar to a closure) [3]. It was found that "users tend to become dissatisfied if mild restraint is placed on their free interaction with the computer." However, "they also tend to problem solve more effectively, using less computer time and less of their own time in the process." The authors suggest that "the results cast doubts on the validity of user acceptance as a general index of system effectiveness."

Clearly, the matter of the responsiveness required of a graphics system is not a straightforward question, and it does require serious consideration on the part of the system designer.* The dilemma is exacerbated by the demonstrated sensitivity of responsiveness to additional investment [11].

Other Indicators

Another effect of the over-reliance by analysts on response time as the sole measure of performance has been the neglect of a number of other important performance characteristics. These have been conveniently divided into task-dependent factors and human-dependent factors [2]. Task-dependent factors include screen size, message size, message format, erasability, color and half-tone capability in addition to response time. These factors will vary with importance according to the particular application; hence a weighting approach should be used when evaluating systems according to these factors.

Human-dependent factors, or more simply human factors, permit the system to be evaluated on its usability by human beings. Such factors include brightness, contrast, resolution, readability and the visual fidelity of the display. These factors are not as importance as they were in the early days of display system design when they were less-well understood, but they should still be validated for any system under consideration. Other ergonomic

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* An interesting application of response time data to a design tradeoff problem is presented in [33].

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considerations might also be important in special cases, for
example if the display were meant for group viewing. Again,
the needs of the particular application will dictate
requirements. A table in [2] presents a cross reference of
desirable characteristics for specific display applications.
Both task-dependent and human-dependent factors are
included.

6. Benefit Analysis

The benefits from a computer system arise from performing
some tasks faster or qualitatively better than previous
methods. Benefits are generally measured relative to the
previous method. The problem is to assign actual dollar
values to the benefits measured.

Methodologies for performing benefit analysis of computer
systems are analogous to the methodologies for evaluating
system performance. There are two general approaches:
empirical test (benchmarks) and parametric analysis.

An empirical test to determine the benefits of a given
system would require two control groups and a typical task.
One group would perform the task according to the old or
baseline method; the other group would perform the task with
the new system. Two types of benefits could be measured
from such an experiment: cost savings from using the new
system to achieve the same level of performance as the old
method, and benefits from any performance levels achieved in
excess of what was normally accomplished the old way.

The other approach of assessing benefits by parametric
analysis involves decomposing tasks into a number of
elements. The benefits from improved performance in each
element must be assessed, and then the old and new system
can be compared on each element. For each application, the
required tasks can be reconstructed from an appropriate
aggregation of elements (where the parameters specify the
proportions for each). In this way the benefits from doing
the particular application with the new system can be
estimated.

Unfortunately, very few published results of either type
of study are extent in the literature. Productivity claims
of 500% and above for the first type of study have been
bandied about at professional society meetings, but the
supporting evidence has not been published, either because
it did not exist in satisfactory form or because such data

was considered proprietary. What are most commonly found are comparisons of an installed system with the old way of doing things, without controls for any other variables. Sackman [28] has presented a summary of several such studies comparing on-line vs. off-line performance on a number of different tasks [1, 9, 12, 14, 27, 29]. The shortcomings of the experimental methodology employed in most of these studies has been critiqued [21].

Occasional studies of the second type have been published, but the focus has generally been so narrow that the results could not be generalized [5]. An example of a better study of this type is Gold's study of problem-solving performance in time-sharing versus batch processing [13].

Gold's Study

Using a programming language available in both batch and on-line environments, Gold "focused on a development of a methodology through which time shared computer system usage could be evaluated." Five categories of variables were included in the methodology:

    Cost of using the system
    System performance
    Turnaround time
    The mode of learning resultant from system use
    The attitudes of the system users

Principal variables associated with the measurement of the computer system features included computer response delays, degree of interaction between the user and the computer system, and quality of response in feedback mechanisms and programming systems.

User attitudes are defined in the study as "the degree to which the computer system characteristics appear to the user to facilitate or hinder him in the attainment of his short and long term objectives." User behavior is further characterized in the study as "the degree to which the user relegates programmable problem solving to the computer system." Performance for the purposes of the study is defined as "a measure of the output of the man-computer system which is arrived at independently of the user's behavior or the computer system used."

The following are the significant findings of the study with respect to user behavior:

1. The users of the time sharing system interacted with their computer system more than three times as often as did the batch-processing users.

2. There was no significant difference between the reasons advanced by the time sharing or batch-processing users for initiating computer actions.

3. There was a strong relationship between a batch-processing user's performance level and the number of computer interactions which produced usable output. For the time sharing user, the correlation between performance and the number of sessions with the time shared computer console is strongest.

4. Much more favorable attitudes toward the time shared computer system, its use and the results produced through it were evidenced.

With respect to quality and cost of results, the following results were reported:

1. Use of the time sharing system resulted in a higher level of objective performance than use of the batch processing system. Also, the "perception and understanding of the problem" of the time sharing users was evaluated as significantly higher than that of the batch users.

2. The total cost of time sharing and batch usage did not appear to differ appreciably. Higher computer costs and lower man costs were found with time sharing usage, however. There were indications that the total cost for equivalent objective performance would have been less for the time sharing users.

A Suggested Approach

Studies of the type just discussed are limited in that they may not be generalized beyond the specific sample activities under investigation. There has been no attempt to decompose the overall activity into more basic application-oriented functions, and to model different activities on the basis of these functions.

Application-oriented functions are different in character than the type of model activities developed by Cislo. For example, text editing and geometric sketching might be two tasks elements which would be used in different proportions

in a particular graphics application. Determining the
benefits of improved performance on each of these tasks
would provide the necessary data to determine the benefits
for an application comprised solely of those two activities.
A sample list of kernel activities for benefit analysis is
presented in Table 2. Other elements need to be identified
and analyzed.

Text Editing - original input and modification
Sketching - original input of geometric data
Updating - modification of geometric data
Inquiry - transaction processing
Directing - on-line control of other operations
Monitoring - of other operations
Mechanization of Output - production of finished drawings
Rapid Turnaround - should be isolated as a separate
benefit

Table 2. Sample Kernel Graphic Tasks for Benefit
Analysis

The paradigm suggested would employ first analysis, then
experimentation, then synthesis and finally validation by
means of experimentation again. The goal is to isolate the
individual task activities in an application, experimentally
determine the individual benefits for each, parametrically
aggregate these benefits to determine the benefits for the
entire application and finally to validate these results by
determining directly the benefits for the entire
application. Since part of the paradigm includes
experimentation using the application in its whole or total
form, an application of limited complexity should be chosen.

Having chosen such an application, it will be necessary
to try to decompose it into discrete task areas. This is a
procedure for which no formal rules exist. Common sense and
some understanding of what constitute "closures"[23] in the
psychological sense will have to guide this analysis. The
activities should be large enough that they may be analyzed
and the benefits from each determined, but they should also
be sufficiently limited in scope that they may be
experimentally manipulated reasonably well and that they may
be used as building blocks to characterize full
applications.

Having chosen the task areas, or kernels, experiments
will be designed after Gold's model to determine the
benefits derived from performing each task on a model

graphics system as compared with doing it some other (baseline) way. Experimental procedures employing two or more sample groups and a control group are well understood and should be followed. Statistical techniques such as analysis of variance may be useful both in establishing the level of benefits and validating the initial choice of the groups.

The final validation of the approach comes after an application is modeled by the task groups and the benefits are predicted and verified by experimentation. This will require an experiment which treats the entire application -- which we have been trying to avoid -- but this is necessary a few times in order to validate the approach. If the approach can be validated, experiments on that scale will not be necessary again.

Studies such as this are but a first step in the development of kernel problems for the assessment of benefit values for particular systems. Many more studies, and preferably a systematic project with the stated objective of disaggregating the application-oriented functions of a graphics system and determining the benefits of each, are required before a parametric approach to determining the total benefits of an arbitrary system can be perfected.

7. Synthesis: Cost-Benefit Analysis

Cost-effectiveness analysis is valuable because it shows how to best allocate limited resources so as to optimize some specific performance objectives. However, such an analysis is inadequate for making an investment decision. Such decisions require that total system cost be compared with the value of the benefits provided by the system. This requires that acceptable levels of performance be defined, so that a point on the cost-performance curve (corresponding to a particular system) can be selected. Comparing total costs with the benefits to be derived from the system determines whether or not the system selected is cost-beneficial. Unfortunately, the problem is rarely expressed this way in the literature.

Cost-Value Technique

One approach which has been described in the literature is the so-called "cost-value technique."[19] This approach describes a formal technique for comparing computer system

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proposals which all offer slightly different features beyond the basic mandatory requirements. The procedure involves assigning a value to each of these "extras" (expressed in terms of dollars) which are credited to the cost of each proposal. The value of expansion potential, for example, is assessed and subtracted from the costs of systems which offer it. The approach is crude and subject to all the perversions of subjective judgement, but at least it forces the evaluators to think in terms of the benefits to be gained from particular features.

Figure of Merit

In another vein, Dunn [8] has sought to define a figure of merit for computer graphics systems which was free of bias towards any particular type of configuration but which is applicable to all types of configurations. However, Dunn claimed that "useful measures for interactive graphics systems are dependent upon subjective judgements." His argument was as follows:

"Any measure that is devised must reflect more than dollar costs and/or usefulness to the human and/or satisfaction achieved via a particular configuration. An interactive graphics system should and does function as an ´amplifier´ of the interactive human activities in conjunction with the use of computers. The amplifying function affects quality of results, quantity of work accomplished, cost-effectiveness of methodology, efficiency of effort, minimization of elapsed time for work efforts, and so on. Amplification in this sense, then, incorporates a variety of dollar costs along with usefulness and satisfaction for the human user."

He suggested a figure of merit called "degree of amplification" or "amplification factor", symbolized as "A!" and based upon four factors: productivity, degree of interaction, extent of graphics capability and total system direct dollar costs per graphics console.

The productivity factor, P, is defined as the change in the rate of units of acceptable output relative to the same function being performed via a non-graphics console. The units of acceptable output are application-dependent (e.g., engineering drawings completed).

Graphics capability is a measurement factor that reflects both ease of use of the graphics console and extent of load on supporting computing systems. The graphics capability

factor, GC, is defined as the weighted sum of capability
indices for all desired features. The index values are 0 if
a desired feature was not available, 1 if a desired feature
was available, and -1 if a required or critical feature was
not available. The weights indicated the relative
importance of each feature.

The degree of interaction is measured by the interaction
quotient, IQ, and is defined as a function of the ratio of
the effective data rate of the connecting channel to the
interaction data flow rate requirement. The IQ is expressed
as a weighted sum of quotient terms for each type of
interaction which could occur. Each term has the form
DR/(DO+DI), where DR is the effective data rate of the
channel and DO and DI are the output and input data rates,
respectively, at the graphics console required to request
and receive response for that type of interactive service
request.

Direct costs are the pro-rata portions of system
resources attributable to graphics support. These include
the fair share of all remote, interconnecting and local
hardware and software that is necessary to implement the
graphics system.

Finally, the amplification factor, A!, was defined as
follows:

$$A! = \frac{d1 \ P \ (d2 \ IQ + d3 \ GC)}{d4 \ \$/C}$$

where P is the productivity factor; IQ is the interaction
quotient; GC is the graphics capability; $ is the total
system direct dollar costs; and C is the number of graphic
consoles that may be concurrently active in the system. The
di are the assigned weights that reflect the significance
attached by installations towards each of these factors. A!
is thus a weighted measure of the change in the rate of
productive output per dollar of total graphics system direct
cost per active console.

A Cost-Benefit Formulation

As has been indicated, the formulation of a cost-benefit
analysis must combine the results of cost-effectiveness
studies and benefit analysis. Cost-effectiveness analysis
identifies those systems with the greatest performance for a
given level of investment, or the least costly system for a

given level of performance, depending on how the analysis is performed. No guidance is provided, however, for the selection of a system from a group of systems at different levels of investment and performance, because there is no way to judge if incremental improvements in performance are worth their incremental costs. Benefit analysis addresses this point by placing a value on improved levels of performance. To perform cost-benefit analysis, the benefits from different systems are systematically compared with their respective costs in a search for the system with the greatest net benefit (gross benefit minus cost).

When cost-effectiveness analyses are performed for a variety of systems at different levels of cost and performance, an optimal price-performance function is obtained. Specifically, this function is obtained either by

    a) successively finding, for different levels of investment, the best level of performance obtainable for each; or

    b) successively finding, for different levels of performance, the least costly system which will provide it.

Whichever procedure is followed, the result is an "efficient frontier" of systems which are optimized at every level both for cost as a function of performance and performance as a function of cost. This frontier may be expressed either as

$$C = f1(P) \qquad (1)$$

    or

$$P = f2(C) \qquad (2)$$

A similar frontier may be obtained from benefit analysis, representing the maximum level of benefits possible for any level of investment. The derivation is easier to visualize for the curve expressing benefit as a function of performance. To obtain this function, the benefits for systems SELECTED FROM THE EFFICIENT PRICE-PERFORMANCE FRONTIER at different levels of performance are successively determined. The result is a function giving the maximum benefits possible for each level of performance. This may be expressed as

$$B = f3(P) \qquad (3)$$

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Cost-benefit analysis seeks the system with the maximum net benefit (the maximum of benefits minus costs). Thus, the problem is to maximize

$$NB = B - C = f1(P) - f3(P) \qquad (4)$$

Typical curves for the functions under consideration are illustrated in figure 11. Very little must be assumed about either function to assure that a solution is possible. The benefit function must exceed the cost function at some point or the system will never even be considered for use. Both functions are also assumed to be asymptotic, for the following reasons:

1) The cost function is asymptotic in the sense that at some point, successive increments of investment provide successively smaller increments of performance. Economists would call this an illustration of the decreasing marginal efficiency of capital. In simple terms, as performance is improved, it becomes more and more costly to provide still better performance.

2) The benefit function is asymptotic in the sense that at some point, successive increments of performance will provide successively smaller increments of benefit. Economists refer to diminishing returns; in simple terms, the more of a good or service is provided, the less is the value of still more of that product.

With these justifications for drawing the curves as illustrated in figure 11, an analytic solution may be obtained by the use of calculus. The desired maximum occurs when the first derivative of the net benefit function is zero:

$$0 = d(NB)/dP = d(f1(P))/dP - d(f3(P))/dP \qquad (5)$$

Subject to $NB > 0$.

Reformulation

Actually, the cost-benefit formulation illustrated thus far has been somewhat simplistic in that it ignores utilization level. Consideration of utilization level is of primary importance because of its effect on the cost function -- increased utilization results in lower average costs. Utilization level may be of secondary importance because of its effect on benefits, e.g., the effects of scale.
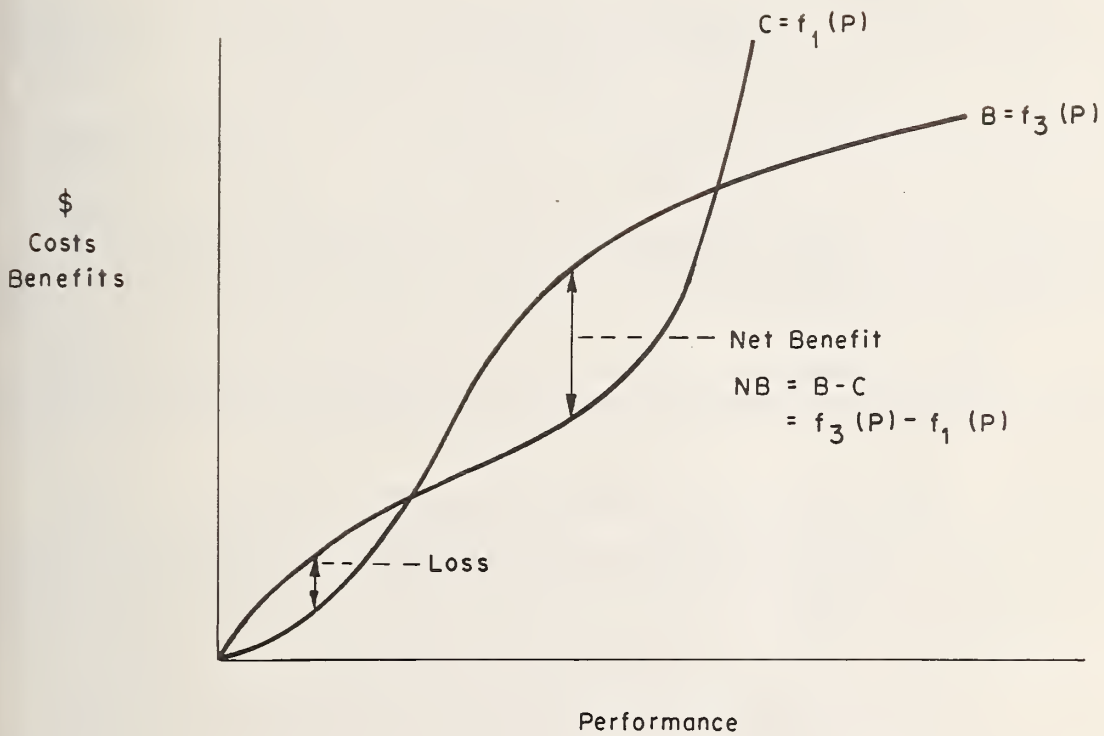
Figure 11. Graphical Presentation of Cost-Benefit Formulation

In the reformulation of cost-benefit analysis, costs and benefits are recognized to be functions of both performance and utilization level:

$$C = f1(P,U) \qquad (6)$$

$$B = f2(P,U) \qquad (7)$$

If the expected utilization level is known, it can be held constant for the analysis and the previous formulation is valid. If it is desired to permit utilization level to vary in the analysis, the graphical formulation can only be expressed as a three-dimensional graph. A solution is insured by arguments similar to those used previously. As utilization level increases incrementally, benefits will also increase, but at some point will increase less rapidly; likewise, costs will decrease, but at some point will decrease less rapidly. Thus, the effect of utilization level is asymptotic both for benefits and for cost.

The analytic solution to this formulation requires the solution of a simultaneous set of equations obtained by setting the partial derivatives equal to zero:

$$0 = \partial(NB)/dP = \partial(f1(P,U))/dP \qquad (8)$$

$$0 = \partial(NB)/dU = \partial(f2(P,U))/dU \qquad (9)$$

Subject to NB > 0.

Comparison With Previous Approaches

The cost-value technique may be viewed as an attempt to adjust for differences in system performances by modifying system cost. The approach is in keeping with the spirit of cost-benefit analysis; it is just too simplistic to be useful in a complex case.

Dunn's approach may be reduced to a form closer to the formulation suggested for cost-benefit analysis. Performance is actually a function of both the interaction quotient and graphic capability. Thus, the figure of merit reduces to a performance function over a cost function. All that is lacking is to relate performance to value, but this is facilitated by the way in which performance is expressed. By expressing performance in terms of productivity gains, it is easy to determine value by considering the value of performance achieved the old way. The unit benefits of the

new system are just the unit value of output done the old way times the rate of increase of productivity.

The real shortcoming off Dunn's approach for the purposes of cost-benefit analysis is that it starts with the data it should be seeking. Data such as the graphics capability factor, the various weights, and in particular, the productivity factor, are unknown in advance. The crux of the problem is to determine the productivity gains from using a particular system. Once this is known, and the cost for using the system is determined, then the cost-benefit ratio for the system can be determined.

8. Conclusions

The quantitative analysis of computer graphics systems is performed at a very crude level of sophistication today. This is partially because it has a basis in the evaluation of computer systems in general, which is still a very inexact science, and partially because it deals with a system involving humans, whose performance is always difficult to assess.

As we have explained, performance evaluation of computer systems in general and graphics systems in particular can be done reasonably well. Cost analysis can be done well also; consequently so can cost-effectiveness analysis. On the other hand, benefit evaluation cannot yet be done very well, so neither can cost-benefit analysis.

Cost-effectiveness analysis is necessary but not sufficient for making investment decisions. Cost-benefit analysis requires the output of cost-effectiveness analysis, since it requires optimal levels of performance for given levels of investment. What must then be added are results from benefit analysis to determine the optimal level of investment. However, procedures for performing benefit analysis are not well-developed. An experimental approach was outlined in this paper which applies the same types of tools to benefit analysis which have been applied to performance analysis.

Still, cost-effectiveness analysis will likely continue to be the principal tool for choosing among alternative systems on the same order of cost or of performance. Cost-benefit analysis is too gross a tool to detect small differences between systems. Cost-benefit analysis will be

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increasingly used, however, to place the "go or no-go"
investment decision on a more analytic basis.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report assesses the state-of-the-art in cost benefit analyses of computer graphics systems and suggests an approach for developing improved methodology. Cost-benefit analyses are distinguished from analyses of system performance in that the latter are directed at optimizing system performance at a given level of investment, while the former are directed at justifying the investment itself.

Computer graphic system design alternatives are first outlined. Then methods of analyzing the performance and costs of computer systems in general and graphic systems in particular are discussed. With this information it is shown how cost-effectiveness analyses may be performed. The next crucial step is to conduct benefit analysis, an ill-defined art. The results of benefit analysis must be combined with cost-effectiveness analysis in order to perform the desired cost-benefit analysis.

An experimental methodology is suggested for better performing benefit analyses of computer graphic systems. A more rigorous formulation of the cost-benefit procedure is then outlined. No attempt is made in this report to actually perform such an analysis.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Computer graphics; cost-benefit analysis; cost-effectiveness; economics; performance evaluation

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