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An Introduction to Cost-Effectiveness Analysis

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An Introduction to Cost-Effectiveness Analysis

by
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RESEARCH ANALYSIS CORPORATION

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FOREWORD

This paper is a written version of a lecture designed to show the basic theory underlying cost-effectiveness analysis and to be a beginning for developing the tools and language that would permit greater ease in use and understanding of cost-effectiveness analysis.

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**An Introduction
to Cost-Effectiveness Analysis**

AN INTRODUCTION TO COST-EFFECTIVENESS ANALYSIS

What I try to do in this paper is to discuss the use of economic analysis as a conceptual framework in assisting military planners and decisionmakers. This involves the systematic examination of the costs, effectiveness, and risks of alternative policies or strategies or courses of action.

In the military these tools are usually used as one class of inputs into development or force-composition decisions. The term "cost-effectiveness analysis" or "systems analysis" is usually used in the application of these tools to military problems. In the natural-resource area, where there is a long tradition of the application of these techniques, the name "cost-benefit analysis" is more common. You may also find the term "operations analysis" or "operational research" or "operations research" usually used to apply these techniques to problems of operations, today primarily in the business and commercial sphere rather than in the military.

What I am trying to do in this paper is to some extent an experiment for me, in an attempt to use what is called in today's educational philosophy "programmed learning." The figures are in very tight sequence, dependent one on the other. Actually it is a kind of blackboard exercise.

The primary ingredients of cost-effectiveness analyses or systems analyses are:

- (1) Objective(s).
- (2) Alternative means or "systems."
- (3) Costs or resources required by each system.
- (4) A mathematical or logical model, a set of relations among the objectives, alternative means, environment, and resources.
- (5) A criterion for choosing the preferred alternatives usually relating objectives and costs.

This categorizes the things that are discussed in this paper.

By objective is meant the establishment or tentative establishment of the purposes of the alternatives among which we wish to choose. This can be discussed in terms of some concept of military effectiveness, some job to be done, or some impact on another society.

The second ingredient, the alternative means or systems, is the heart of these kinds of analyses. The philosophy simply is that there is a choice, that objectives can be reached by alternative means, and that the problem is to discriminate among alternatives and select the preferred alternative. In the course of doing that, alternatives that can achieve the objectives must be designed and cost or resource consequences must be attached to each of the alternative means.

In the course of performing the analysis, or perhaps synthesis might be a better term for it, we try to relate each alternative to the objective through some form of intellectual exercise that can be called a "model" or a "set of calculations" that may include in its context very fancy war games.

We try to establish the relations among these, and having done that apply a criterion that may be: given a certain objective, which alternative is the cheapest way of achieving the objective? Or, conversely, for a given level of applicable resources, how far does spending this on each alternative get us toward our objective? We either maximize accomplishment of the objective for a given cost, or minimize the cost for achieving a given objective.

With this description of the subject area of cost-effectiveness analysis, I am now going to take you back to freshman or sophomore economics and try to explain what the economic approach is, partly, perhaps, to add to your kit of tools and techniques but also to give you an understanding of the way in which an economist thinks about these problems. We economists think of these as economic problems and apply the tools of economics, although we deal with a different subject matter when we move into military decisions. Many of the people that you deal with, who talk about or practice cost-effectiveness analysis, are professional economists who are bringing a particular way of thinking and a particular language into the arena of measurement and decision. I think it may be helpful for you to see where this springs from.

My exposition is broken into very short steps, but it is important that you follow each one because they are interdependent. We will start with things that are extremely obvious, and I hope we will end with things that are at least fairly obvious.

Figure 1 shows a problem, an industrial firm determining the appropriate mix and quantities of the factors of production. In this case I arbitrarily call them labor and machinery. We are measuring in physical units the amount of input of machinery and of labor on the axes. The numbers in the field represent different levels of output that are achievable with different mixes of inputs. Thus, if the units of labor are held constant and units of machinery are added to these, progressively higher outputs from the results should be expected.

Similarly, in Fig. 2, if the quantity of machinery is kept constant and labor is added to it, progressively higher outputs would be expected.

The two could be combined and units of both machinery and labor could be added, and increasing output would again be expected (Fig. 3).

Figure 4 attempts to cover all possibilities to show what varying combinations of labor and machinery can produce.

If contour lines connecting these points of equal output are now drawn, curves (Fig. 5) that in economic jargon are called "isoquants," meaning equal quantities, are obtained. As we move to the upper right we get points of increasing output.

Let's clean the dots off the figure and work simply with the designations of output along these contour lines or isoquants (Fig. 6).

This is the first piece of information or the first tool that we are going to work with in solving the problem of the proper mix of labor and machinery. Thus far we haven't discussed anything at all about costs and budgets, so let's move over into that arena.

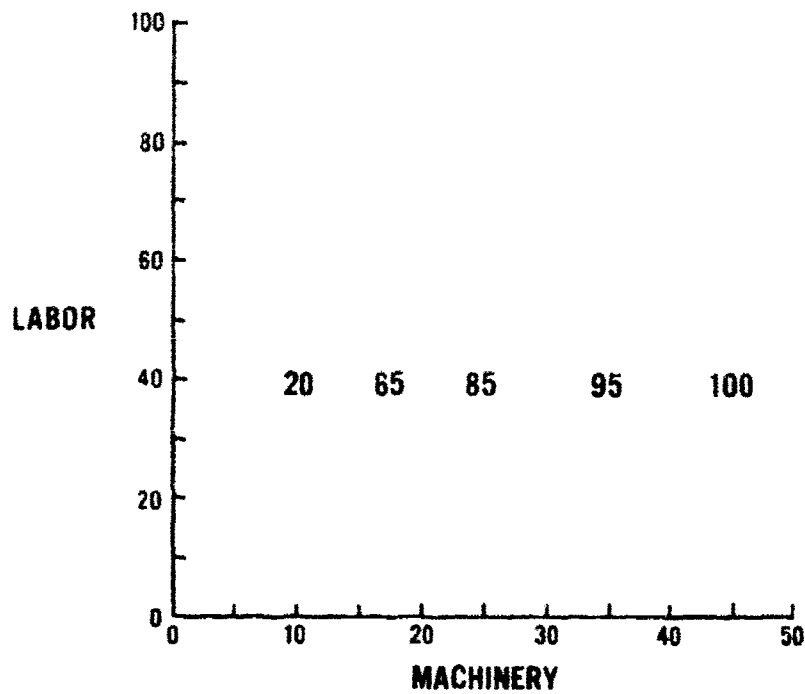


Fig. 1—Effect on Output of Increasing Units of Machinery

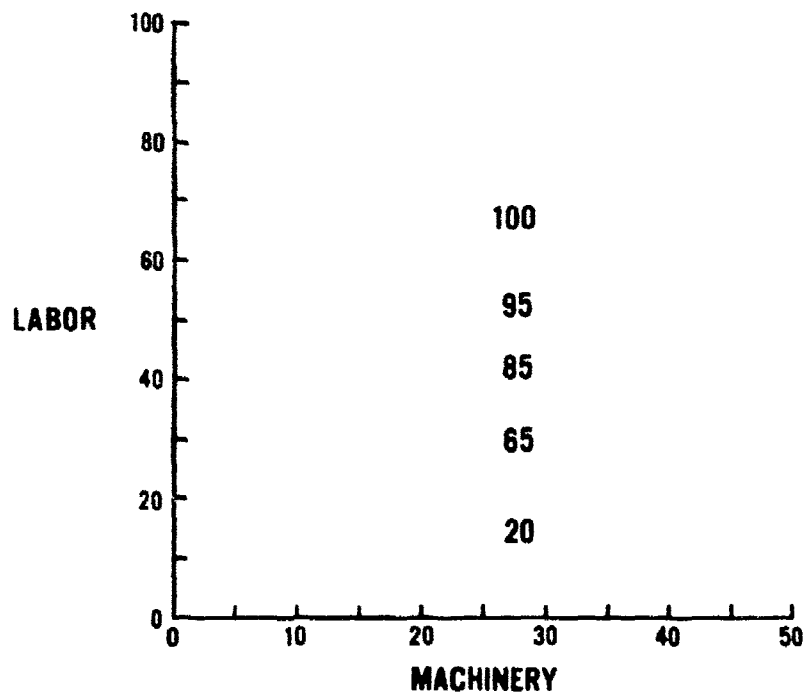


Fig. 2—Effect on Output of Increasing Units of Labor

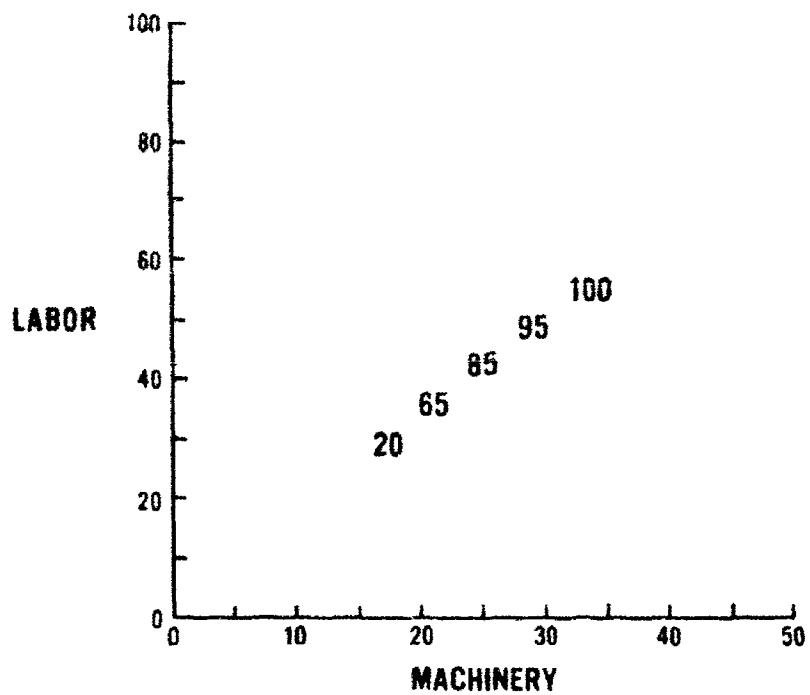


Fig. 3—Effect on Output of Increasing Units of Labor and Machinery

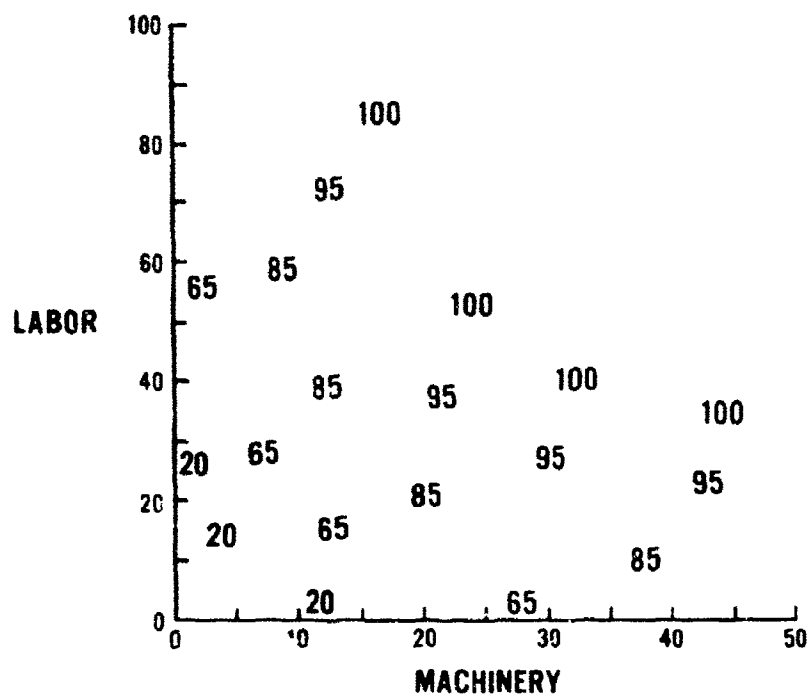


Fig. 4—Effect on Output of Various Combinations of Labor and Machinery

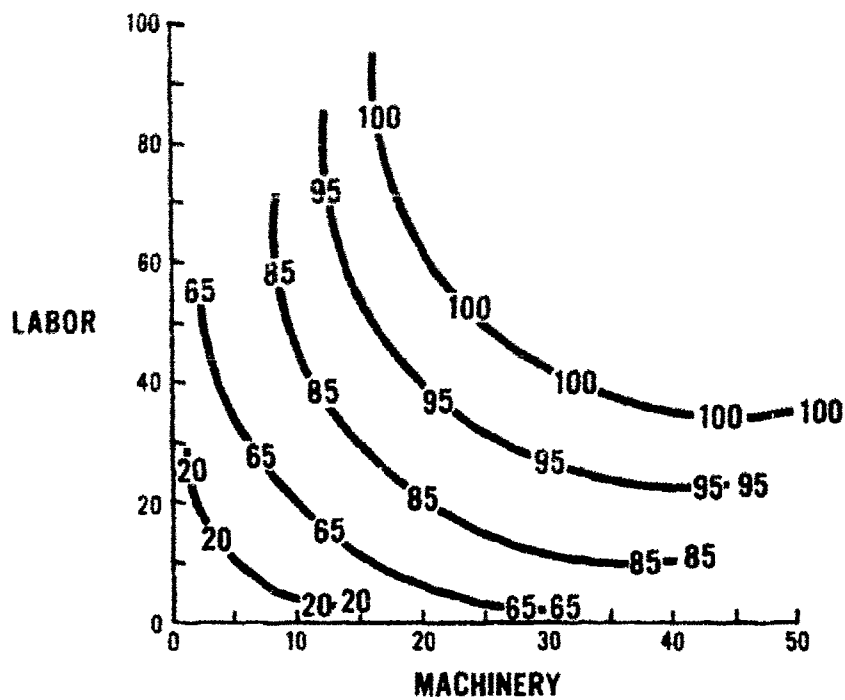


Fig. 5—Derivation of Equal-Output Lines

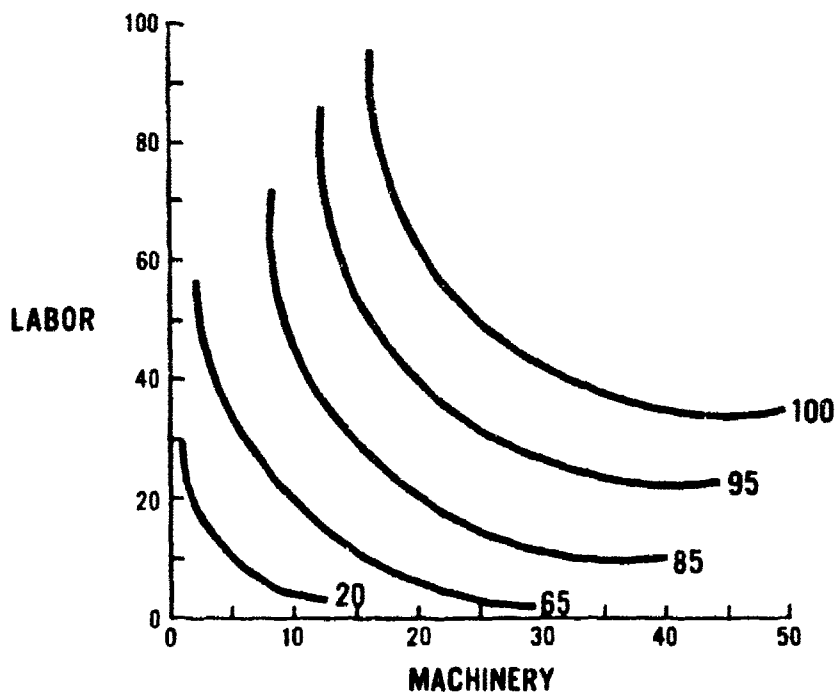


Fig. 6—Equal-Output Lines

We start off with some arbitrary assumptions that labor costs \$5 a unit and machinery \$10 a unit, and the firm, over the time period under consideration, has a budget of \$400 to spend. If we spend it all on labor at this price we can acquire 80 units of labor, or all on machinery at this price we can get 40 units of machinery (Fig. 7).

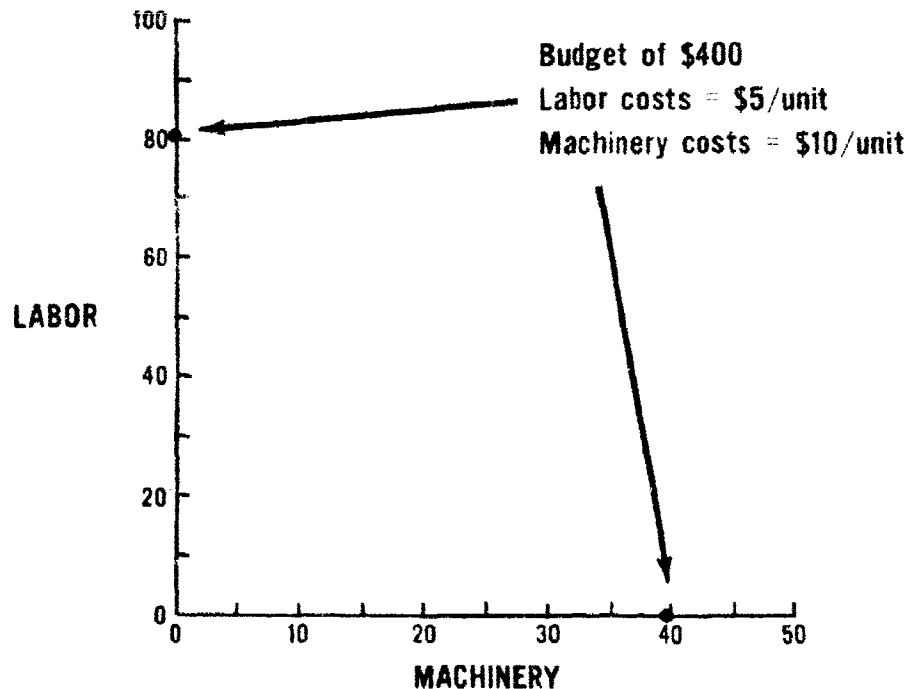


Fig. 7—Limits of Allocation of Budget to Labor or Machinery

We could, of course, compromise, and use 40 units of labor plus 20 units of machinery, as shown by the dot on the line on Fig. 8 and still stay within the budget of \$400. The line drawn on Fig. 8 simply connects all those points where \$400 for labor and machinery can be spent, and this will be referred to as an “equal-cost” or “budget” line.

A whole series of these can be drawn under these price lists for various levels of budget. In Fig. 9 these are straight lines simply because the prices have been kept fixed. If the costs of factors of production shift with the quantities that we buy, these would not be straight lines but would be curves.

Let's begin merging the two concepts, the output-contour lines and the equal-cost lines. In Fig. 10 we have taken one of these curves and a level of output of 85 units and have plotted it on the same graph as the budget lines and ask the question: What is the cheapest combination of labor and machinery that we can use to produce an output of 85 units of our commodity—jelly beans, or whatever we are producing?

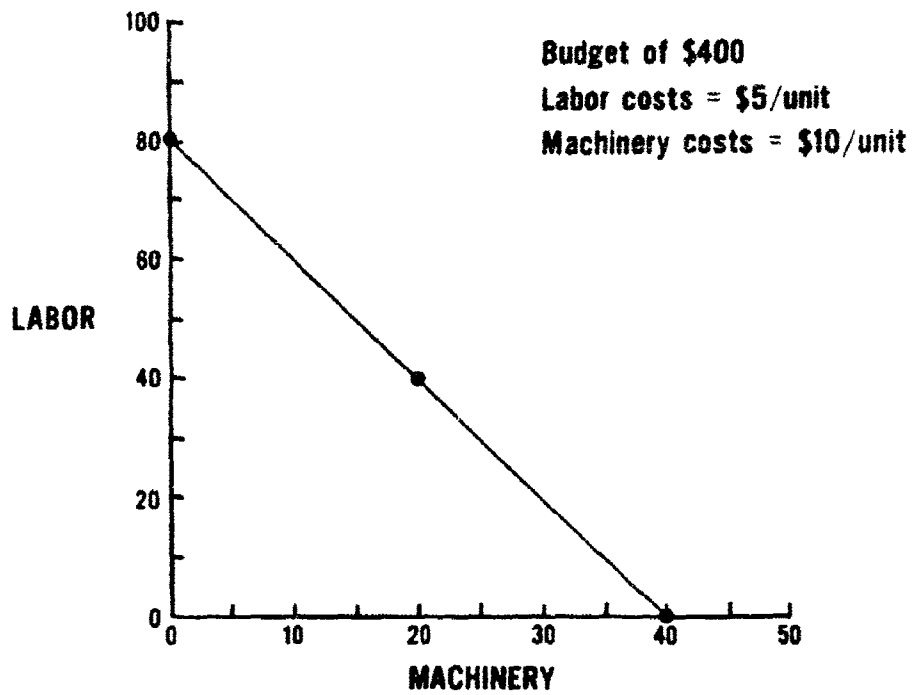


Fig. 8—Budget Line for Combinations of Labor and Machinery

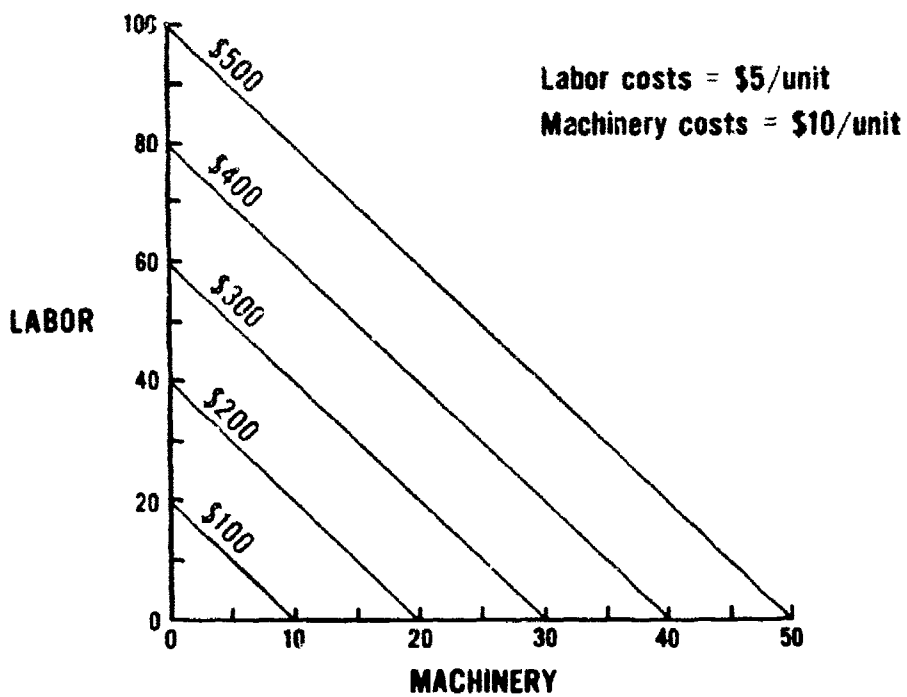


Fig. 9—Budget Lines at Various Levels

Using Fig. 10, the answer shows up that the cheapest we can hope to reach is \$300. Any other combination of labor and machinery that will produce an output of 85 units costs more. You can produce 85 units by using about 35 units of machinery instead of 17 units, but this is going to cost \$400 when you can do the job for \$300. Similarly you could use more labor and produce 85, but at a cost over \$300.

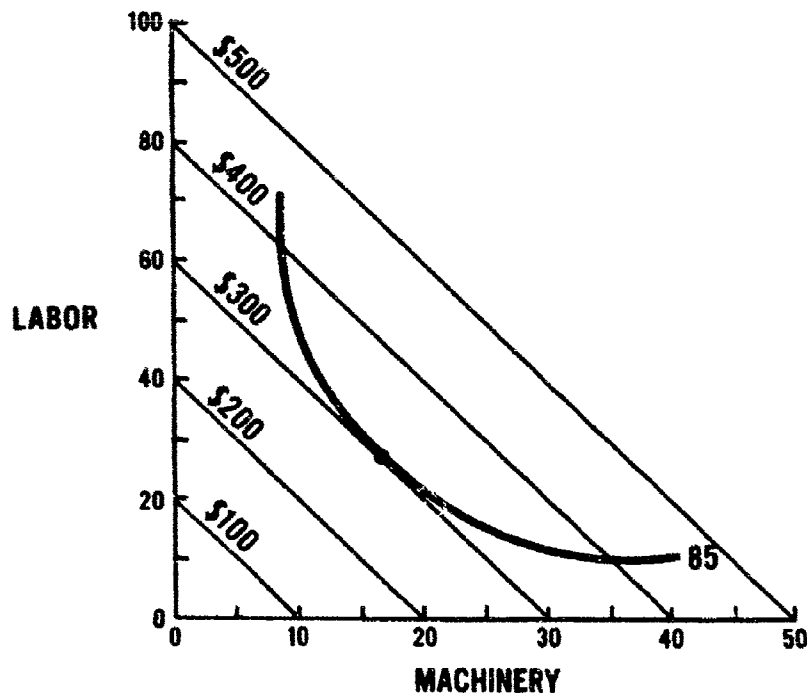


Fig. 10—Various Budget Lines and an Output-Contour Line

Looking at the same problem just the other way, one can ask, given a budget of \$400 as in Fig. 11, what is the greatest output that can be achieved? Again the answer, given the way we set these curves up, is a tangency solution. In this case, 95 units of output are the most that can be made for \$400. You can spend the \$400 in many ways, but, as you move to the right or the left of the tangency point, you are getting less and less output.

Putting all this together (Fig. 12) when all the output possibilities (or rather some from an infinite range of possibilities) are plotted at varying budgetary levels, we have the information to determine the optimal combinations of factors of production for each and every possible budgetary level and for each and every output level.

This assumes that we know two things: (a) the relation between the factors of production and output—something the economists call the “production function,” and (b) the prices of the inputs that are required.

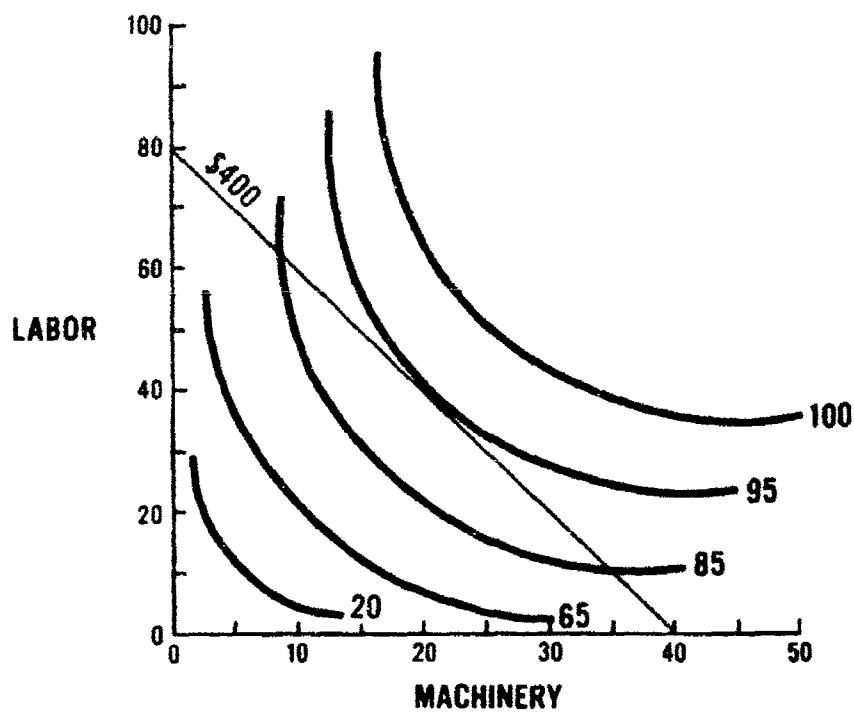


Fig. 11—Various Output-Contour Lines and a Budget Line

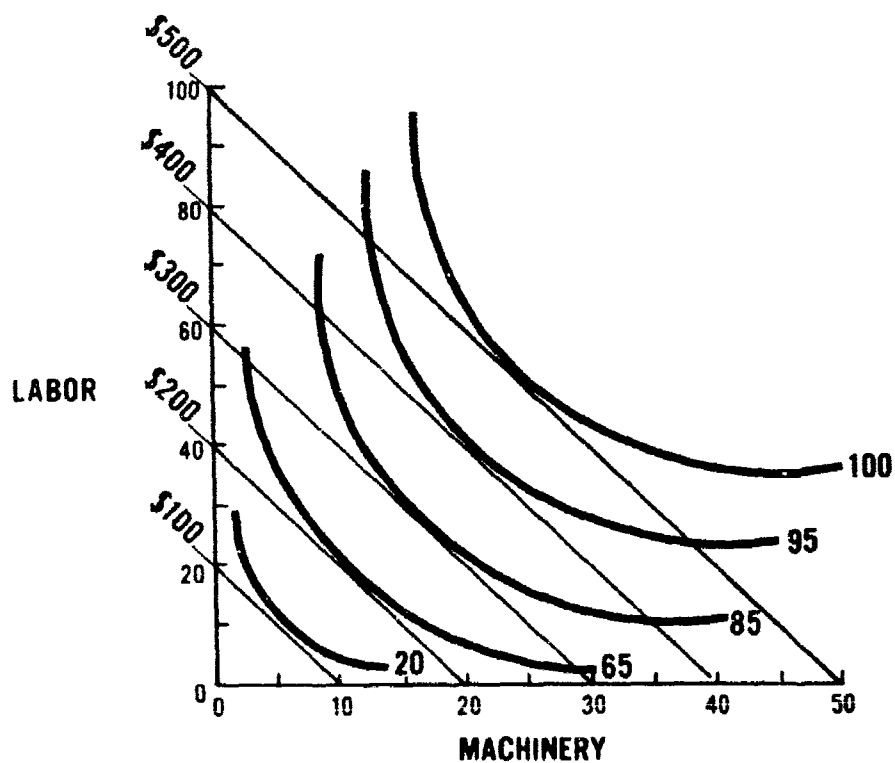


Fig. 12—The Set of Budget Lines and the Set of Output-Contour Lines

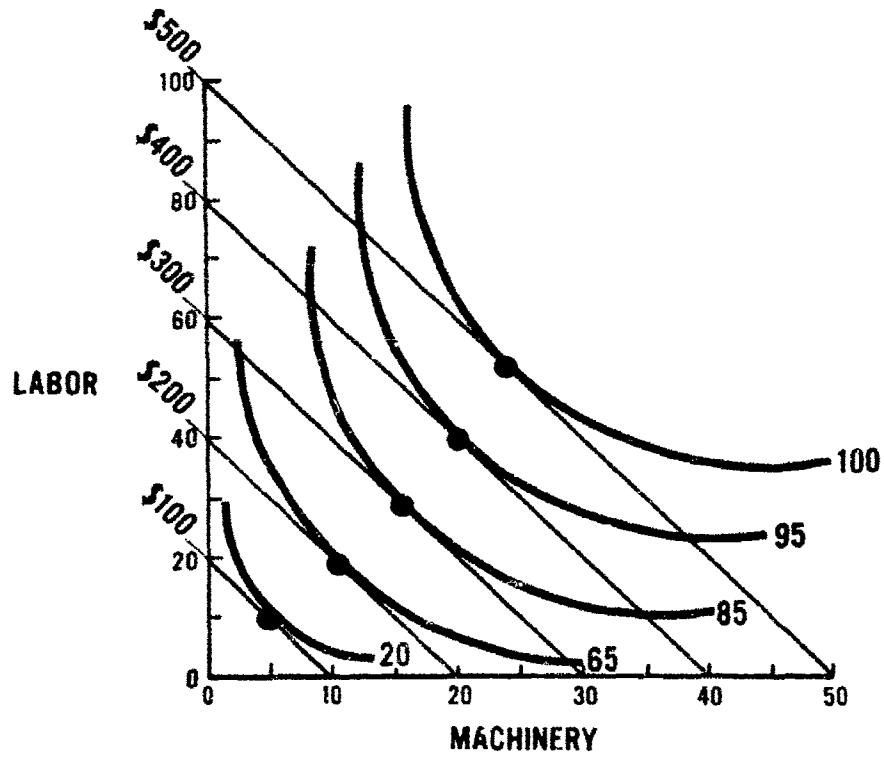


Fig. 13—Least-Cost Points for Level of Output

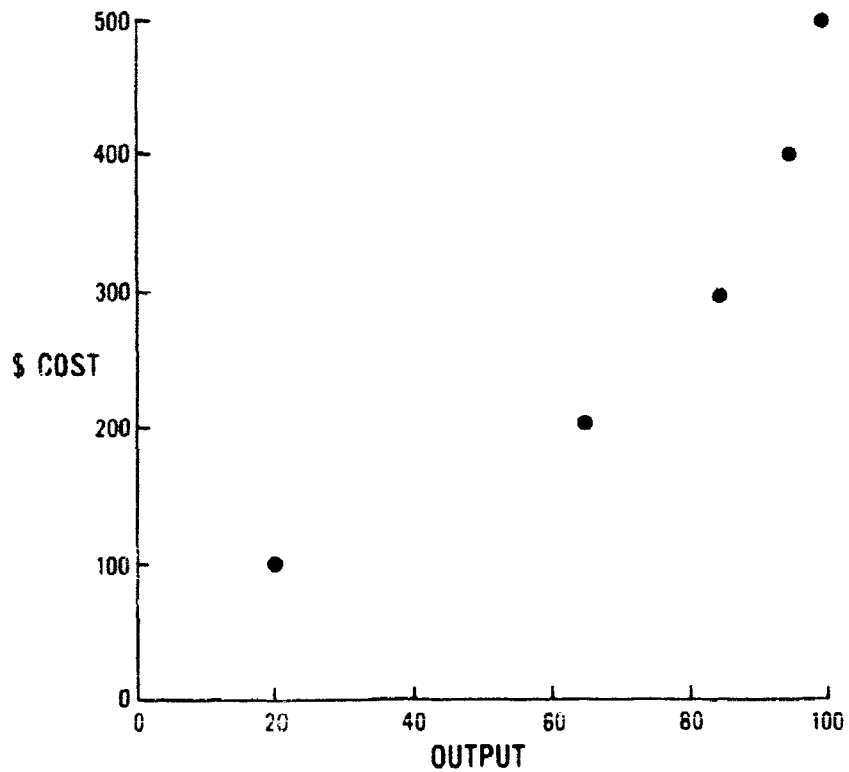


Fig. 14—Points of Minimum Cost or Maximum Output

Knowing these things, we simply plot (Fig. 13) each point that represents the greatest output for a given expenditure or the least cost for any level of output. Then these cost and output points are plotted on Fig. 14 on a different scale.

If these are connected and extrapolated to where other points are likely to be (Fig. 15), we have what is known as a "total-cost curve." This represents the minimum costs at each output level. Obviously one can spend larger amounts to produce the same outputs, by using other combinations of factors. The curve represents the minimum costs for producing any given output, presumably the costs that a rational producer would utilize, or it represents the maximum output that can be achieved at any given level of expenditure.

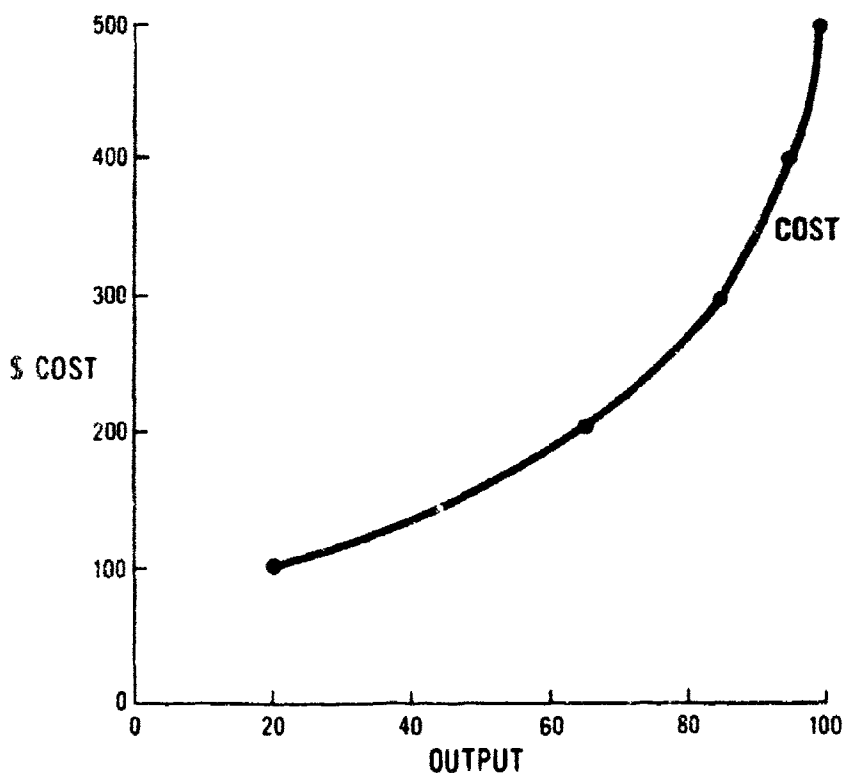


Fig. 15—Cost Curve

The next question then arises in industry: Given this information what level of output do I select?

Another piece of information is needed for this, and that is: What is the revenue or income that can be secured from the sale of the output?

Now, if we assume that the output has a price of \$5 a unit, we can plot another line, known as the revenue curve, which tells us what the gross income would be at various levels of output (Fig. 16).

If we further assume that the objective of the enterprise is to maximize profit, which will be defined as revenue or gross income minus cost, we can now search these curves for the point of the greatest positive difference between revenue and cost. The enterprise selects as its point of production or rate of production that output which maximizes profit, and this works out to about 65 units (Fig. 17).

As far as the enterprise is concerned, there are no more decisionmaking problems with respect to the level of output. We can now translate this choice back into what we set as our problem, the mix of factors of production.

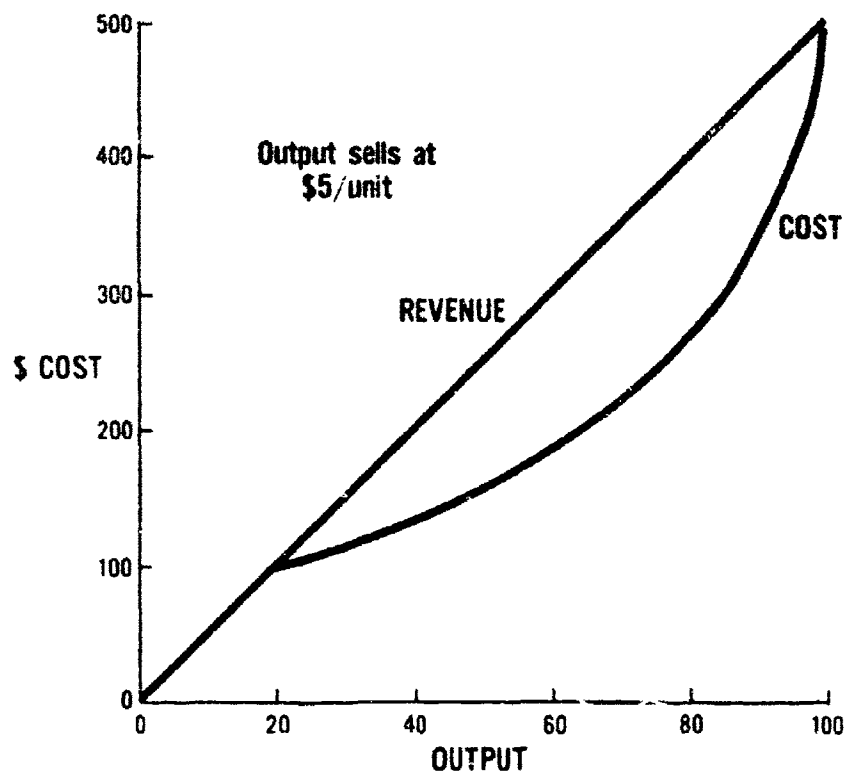


Fig. 16—Cost and Revenue Curves

Going back to one of the earlier charts, we can now read off the number of units of machinery (10) and the number of units of labor (20) that result in the most satisfactory solution for the enterprise (Fig. 18).

Now, I have gone through all this, which is fairly tedious and elementary economics, because it does form a large part of the background of what we talk about when we say, "Let's do a cost-effectiveness analysis."

Let's look at a hypothetical military problem. In this case the problem might be observation aircraft. We are concerned with what number of fixed-wing aircraft and what number of helicopters should be procured. If we can arrive

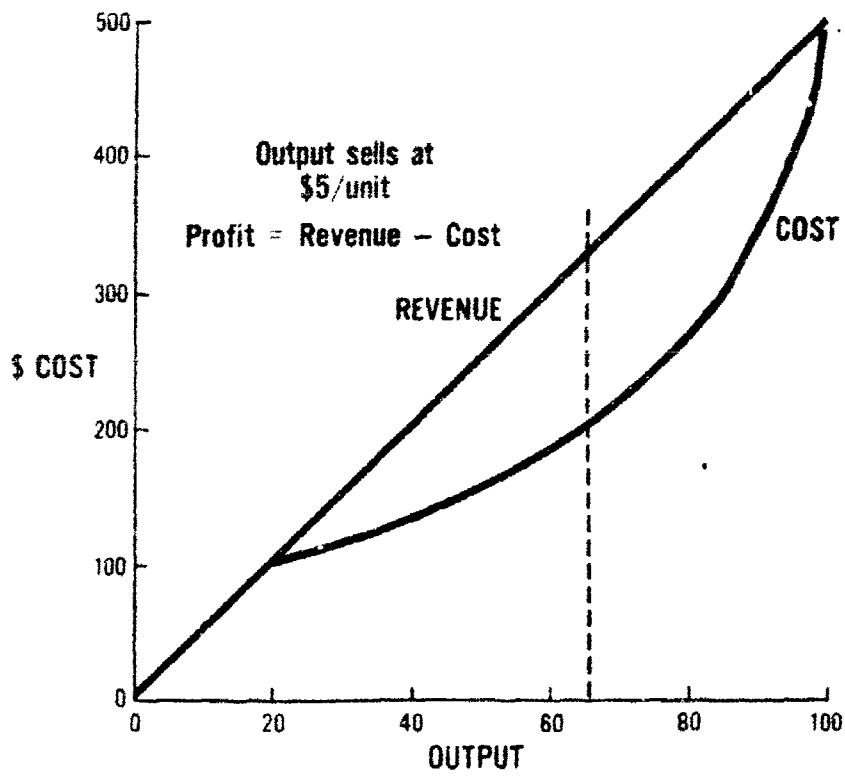


Fig. 17—Determination of Output for Maximum Profit

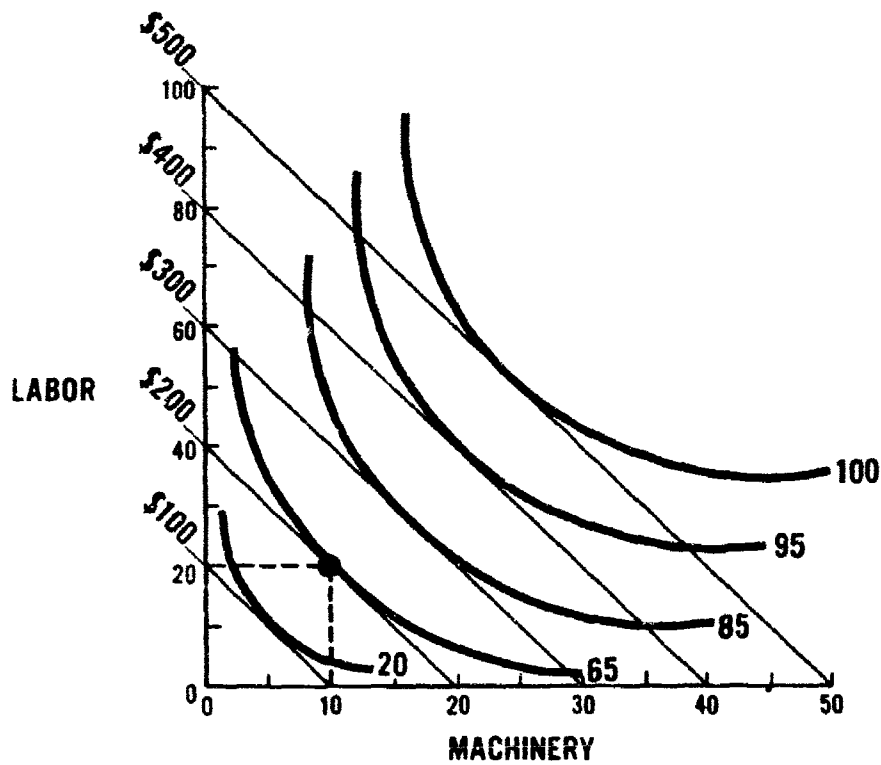


Fig. 18—Determination of Most Satisfactory Mix of Factors of Production

at some concept of output, or, in the terms that are used here, of military effectiveness that can be measured in some fashion, such as numbers of satisfactory missions accomplished during a campaign per day, we can get some feel for the usefulness of these things. If we can then make the measurements of the cost of the various items involved, we can arrive at the same kind of cost-output relations as we did in the case of labor and machinery (Fig. 19).

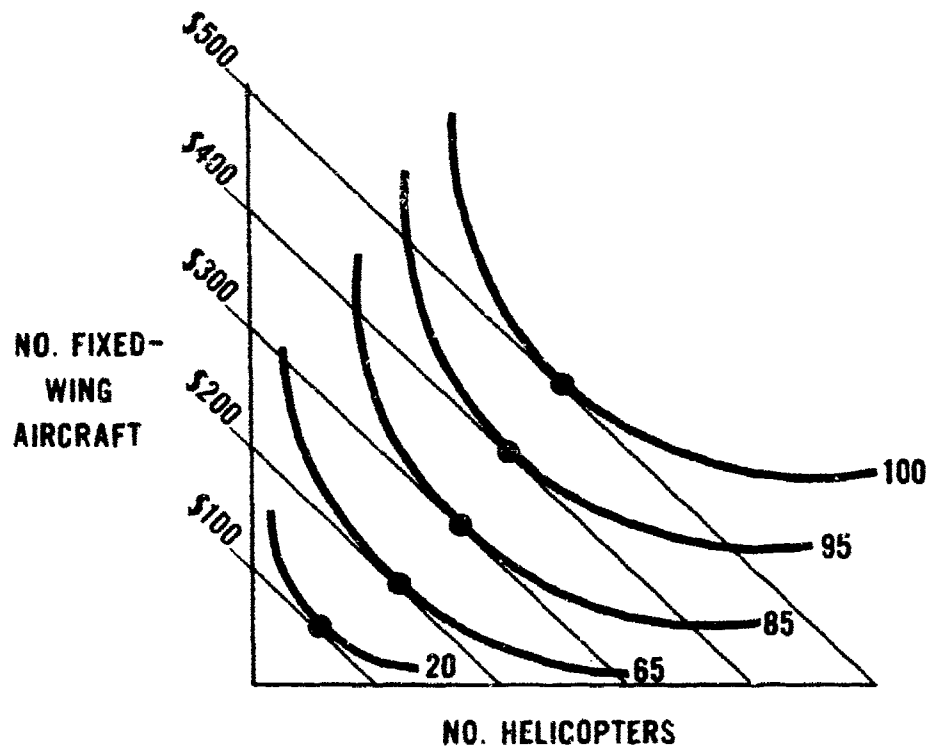


Fig. 19—Military Counterpart to Manufacturing Illustration

At a given cost or a given budget, we can read off the highest output, the highest effectiveness, that can be reached. If we set a level of effectiveness of, say, 85, then the least-cost solution is a budget of \$300, or, more realistically, of \$300 million. This is the lowest that one can arrive at to accomplish the objective.

Conceptually, thus far, there is not a great deal of difference between the industrial and military analyses. I want to stress the assumption that we can in fact measure effectiveness, that we can in fact measure cost. I think you will discover—those of you who have been in the business or are going into the business—that the things I am talking about are perhaps the easiest parts of the job—essentially structuring how one thinks about these things. The tough problem is to implement this structure by getting reasonable, believable measurements.

Let me take this a few steps further. We can now in the same fashion as we did for the problems of the firm consider the spectrum of cost and effectiveness levels. We now can read from Fig. 19 and know for any level of effectiveness what the minimum cost will be. These are plotted and a curve drawn—Fig. 20. Now, if the problem has been set so that there is a fixed budget that can be allocated to observation aircraft, all we need do is read that level off here to know what effectiveness will be achieved. The optimal solutions are

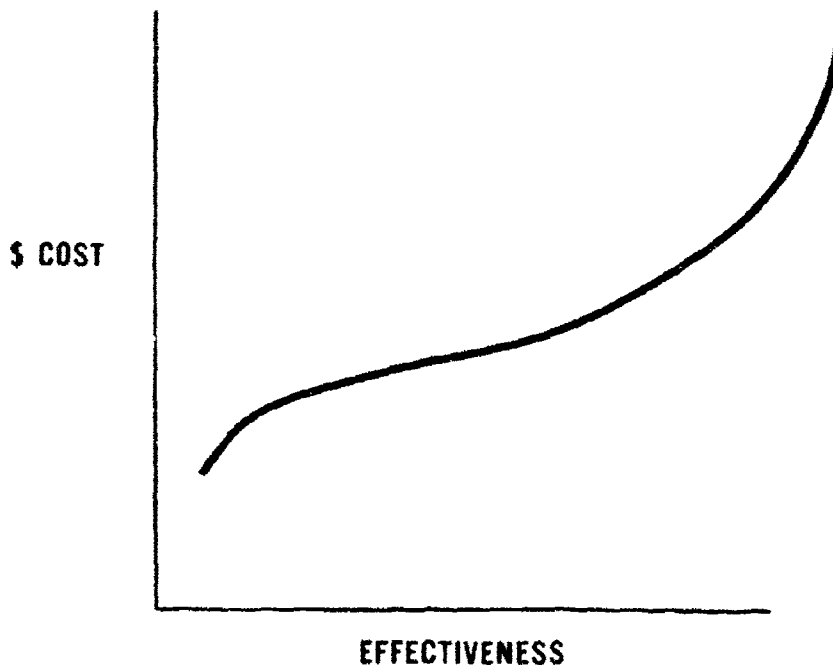


Fig. 20—Curve of Minimum Cost for Any Level of Effectiveness

determined, and we can now go back to our previous chart and read off the appropriate mix of fixed-wing aircraft and helicopters. Similarly, had a level of effectiveness been set, the proper mix and quantities could also be determined.

A more difficult question is: How many shall we buy with no firm budget or effectiveness goal?

This question arises particularly in force-composition problems, and we just don't have enough information to make that decision from this graph and from the work we have done so far.

We lack the revenue curve, the market for our output. Let us assume that, while we were working on the observation-aircraft problem, the fellow in the next office was working on another cost-effectiveness problem.

In this case he was trying to determine what the proper mix should be or what to select between tube artillery and missile artillery, for the purpose, of let's say, our close support of ground forces. He had gone through the same sort of analysis for tube artillery (Fig. 21) that we had gone through on observation aircraft and he came out with various costs and effectivenesses.

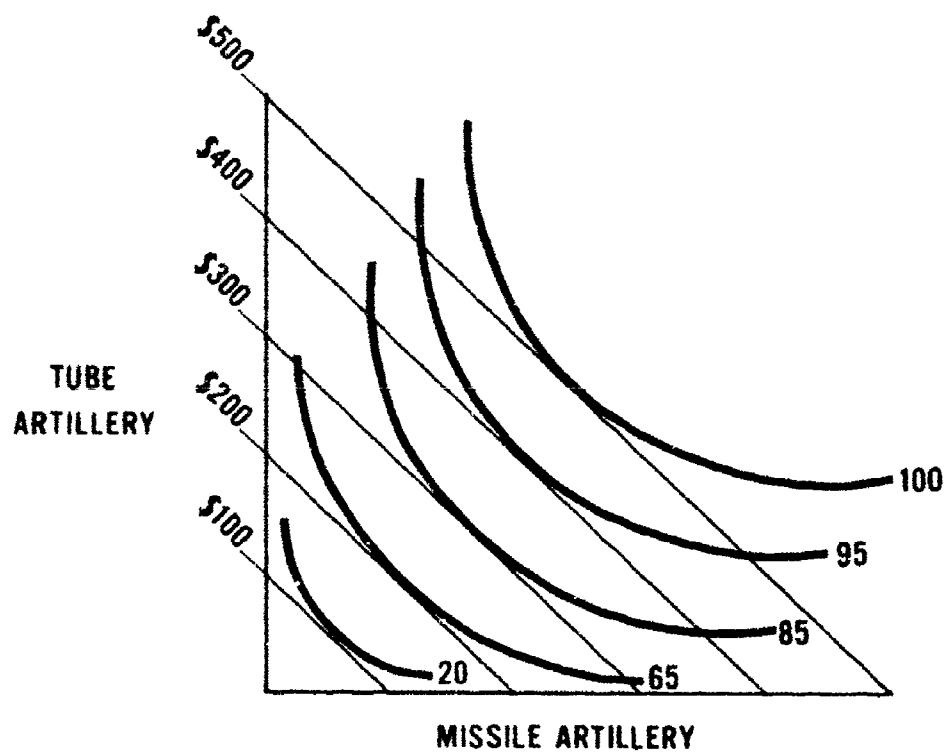


Fig. 21—Equal-Cost and Equal-Effectiveness Lines for Tube and Missile Artillery

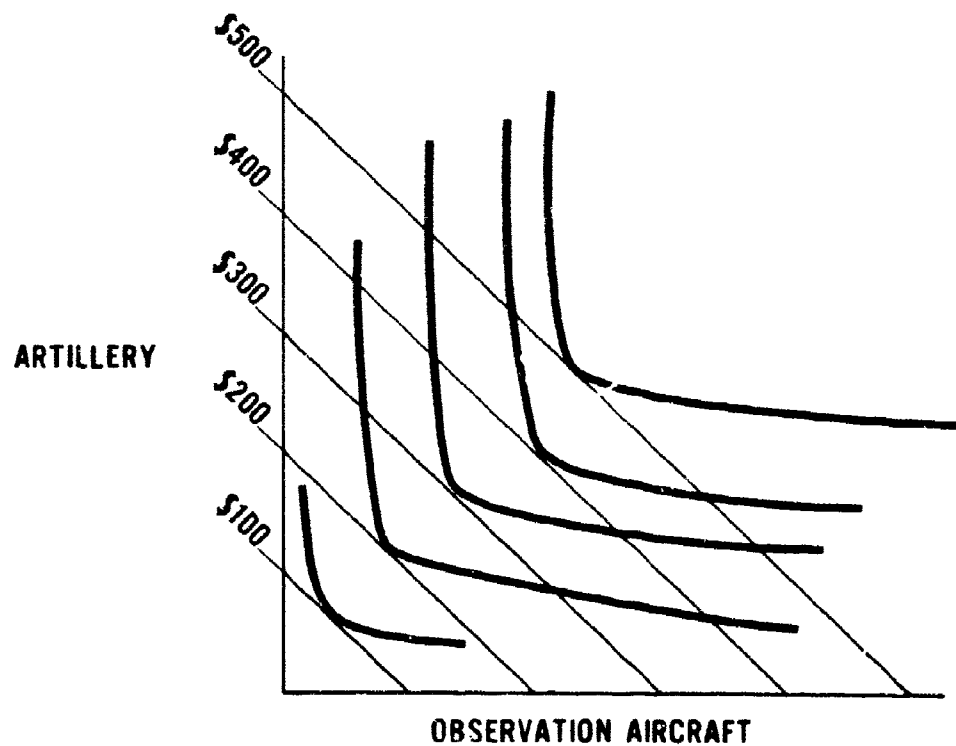


Fig. 22—Equal-Cost and Equal-Effectiveness Lines for Artillery and Aircraft

If the problems were set up or formulated in such a fashion that by effectiveness we were talking about the same objectives with respect to artillery as to observation aircraft, i.e., to assist in holding a certain amount of ground, or to contribute to the destruction of a certain number of targets, or whatever, then it might be possible to merge the two solutions. We would now know for every level of effectiveness to be achieved what the optimal mix of aircraft is, and if we do this properly we now know something about the optimal mix of artillery, so we can put these two together as in Fig. 22.

Frequently we are able to do this. The key to this is whether the outputs we are concerned with are commensurable, i.e., measurable in the same terms. One kind of measure of effectiveness that I mentioned earlier, the number of missions performed, would not be a satisfactory output dimension or effectiveness dimension when we are trying to trade off between aircraft and artillery.

This is a fairly touchy point that you will frequently find in analysis. It is not always clear that the measure of effectiveness with which you are working is really an output or whether it is an input. From many points of view the capabilities of a weapon are only inputs into the determination of the capabilities of the force.

Now, you may have heard of the term "suboptimization." What is meant by this term is that at certain levels—we'll say at the level of the tactical reconnaissance mission—we can decide what the mix of preferred carriers, platforms, and the like, should be. But this does not help you to answer the question I posed: Should you buy any of them, should you buy some, or should you buy a lot of them?

As you move toward considering more and more complex, interrelated systems, you are essentially optimizing at higher levels, but almost always you are engaged in some form of what is termed "suboptimization," as at higher levels our systems are components that may be in a substitutable relation with others.

You may have noticed these curves look a little different from the preceding curves. The weapons that we are talking about are not as nearly simple substitutes for one another as one type of aircraft for another. They also have a strong complementary relation, i.e., the existence of one makes another much more valuable. For that reason, among others, the use of cost-effectiveness as a ratio is frequently deceptive, and very often it is very wrong. As we change the mix of the weapons we are looking at, the usefulness, the utility, the gain, the effectiveness of adding another unit or organization containing these weapons may shift. What we are showing here is a situation very close to that which says there is a relatively close complementary relation between these two. If they were completely complementary, having no capability of substitution, these curves would be at exactly right angles.

What we are talking about here, in simple terms, is that, if we use very much artillery, one could begin to improve the force composition, perhaps, by reducing the amount of artillery and adding target acquisition aircraft. Once we recognize that there are tradeoffs between them, these alternatives should be examined in a cost-effectiveness analysis.

Now let me take this optimization question one level higher. Let's assume that one way or another we solved the problem of how to conduct the land warfare. Obviously I have simplified it very much in taking just a few of the tools.

We've now got a curve that relates the cost to the effectiveness in the tactical area. Somewhere across the hall or across the building somebody else has been doing the same thing for strategic weapons (Fig. 23). Now suppose these two analyses have been performed and the measurements are fine and believable. What now? How do we determine the proper mix?

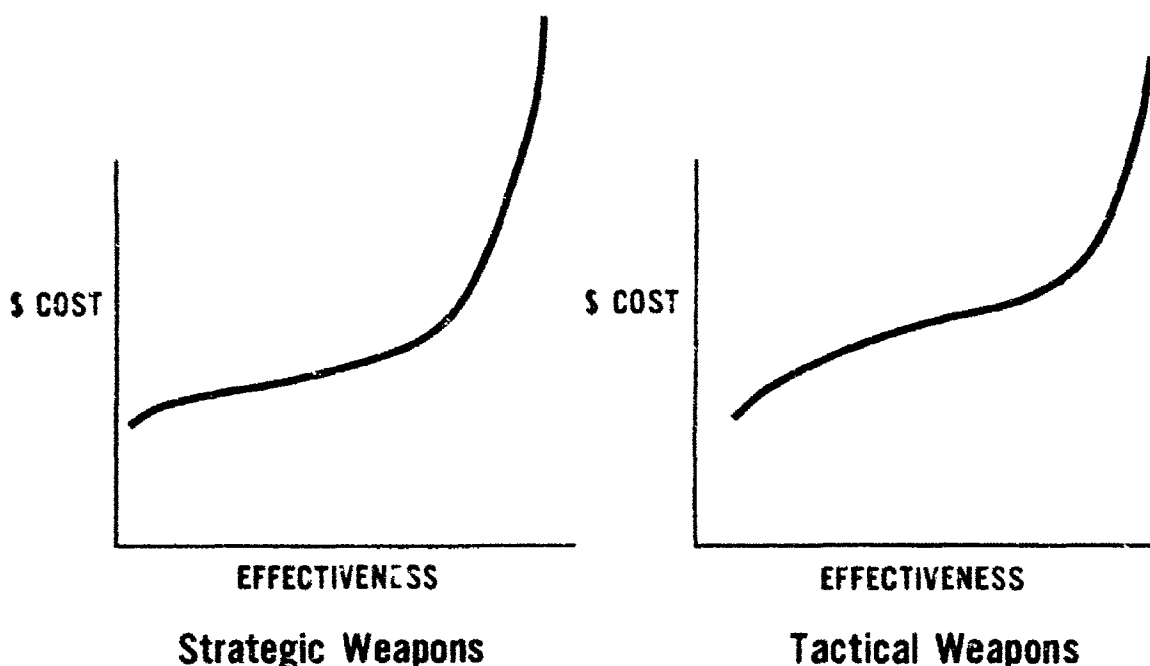


Fig. 23—Comparison of Strategic and Tactical Cost-Effectiveness Curves

I used the word "commensurable" (measurable in the same terms) a little while ago, and I think in the concept suggested by this word lies a key to the roles of the analyst and the planner or decisionmaker. The analyst makes measurements and reduces them to as few incommensurables as possible.

The planner or the decisionmaker, among his other jobs, has the job of interrelating and making commensurable those things which are incommensurable from a quantitative and an analytical point of view. Analysts don't have the information or the techniques to say how much strategic capability is worth relative to tactical capability.

Now a few other measurements that can be added to this might assist the decisionmaker. Suppose we take the same graph. I am hypothesizing here that this may show a situation in which our Defense Department was in, say, in early 1961. Teams might have been set up to examine strategic weapons and tactical weapons, and asked to assert not simply what these relations were but also what the present levels of capability might be today. They plotted points such as those in Fig. 24.

A decisionmaker, looking at these, might have concluded from knowing where on these curves we were, even though the analysis could not tell how much strategic capability was worth vs tactical capability, that additional expenditures in the strategic area would buy very little additional usefulness and that reductions in costs might result in large sums of money becoming available for spending elsewhere, with relatively little degradation in effectiveness.

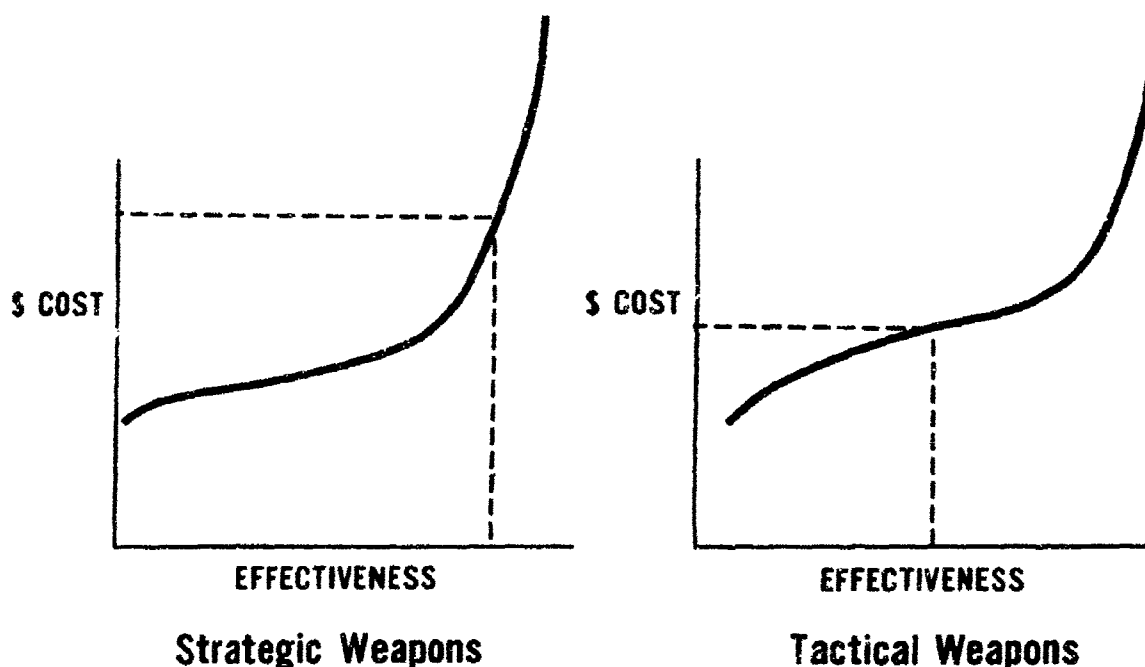


Fig. 24—Use of Cost-Effectiveness Curves To Aid Decisionmaking

At the same time a glance at the tactical chart may have shown the reverse implication, that for relatively small increments of dollars you could get relatively large increments of effectiveness.

Now, if this were so, and the decisionmaker could in his mind get some feel for the relative worthwhileness of these activities, it is possible that the knowledge of the shapes of the curves at the points representing our present program would be helpful in arriving at a decision.

Let me note a few more points and then give you a few examples that address the problem of how to attack the measurement of effectiveness and cost.

I didn't want to leave you with the feeling that the curves I drew originally were the only forms that there were. We talked earlier about right-angle curves that represent complementarity; I now want to show some different curves.

Figure 25 shows a hypothetical situation where there is no complementarity between the weapons. Our equal-effectiveness curves are here straight lines. They are pure substitutes one for the other. In this case the solution is pretty

simple: at any level of effectiveness (or cost) only one weapon system will be chosen. It's obvious from the way the output and cost lines are drawn that it is always going to be cheaper in this case to use missiles. You get the same effectiveness with missiles at \$200 that you get from bombers at \$300, and any mix is in between in cost. You can get the effectiveness cheaper and cheaper by trading bombers for more missiles until you get a pure missile force.

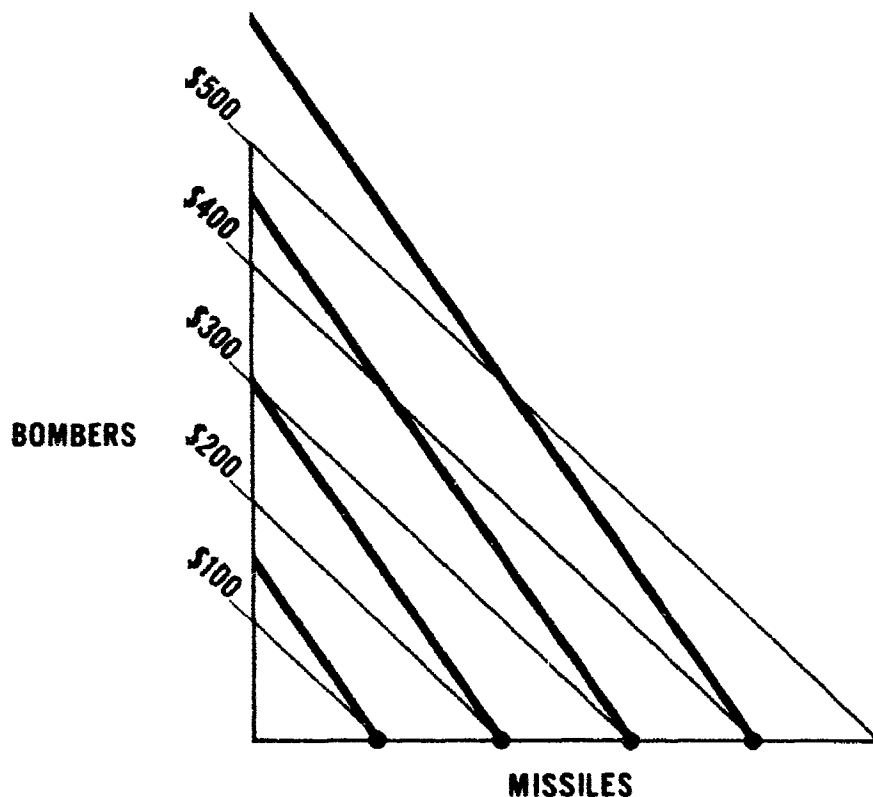


Fig. 25—Equal-Effectiveness and Equal-Cost Curves—No Complexity

One can look at the same kinds of things and get further confused. Figure 26 shows a situation where at low levels of output or low levels of required effectiveness the missiles are cheaper. As we increase the output the output lines begin to change slope. There is a question mark along one line where the output and the cost lines are parallel to one another, which means that it doesn't matter for the purposes of this analysis what mix is bought. Any mix does the same thing at the same cost. At higher levels there is the situation where bombers become cheaper than missiles.

This kind of situation results in cost-effectiveness charts such as Fig. 27, with crossover points, and the analyst doesn't know whether to recommend missiles or bombers if he doesn't know what size forces or budget levels may be set.

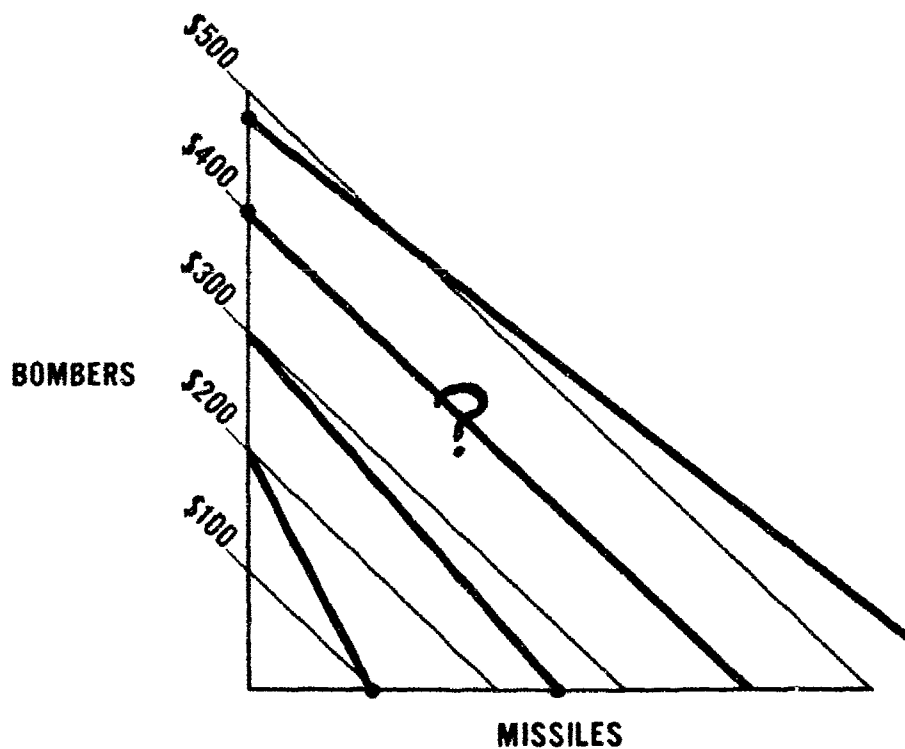


Fig. 26—Equal-Effectiveness and Equal-Cost Curves

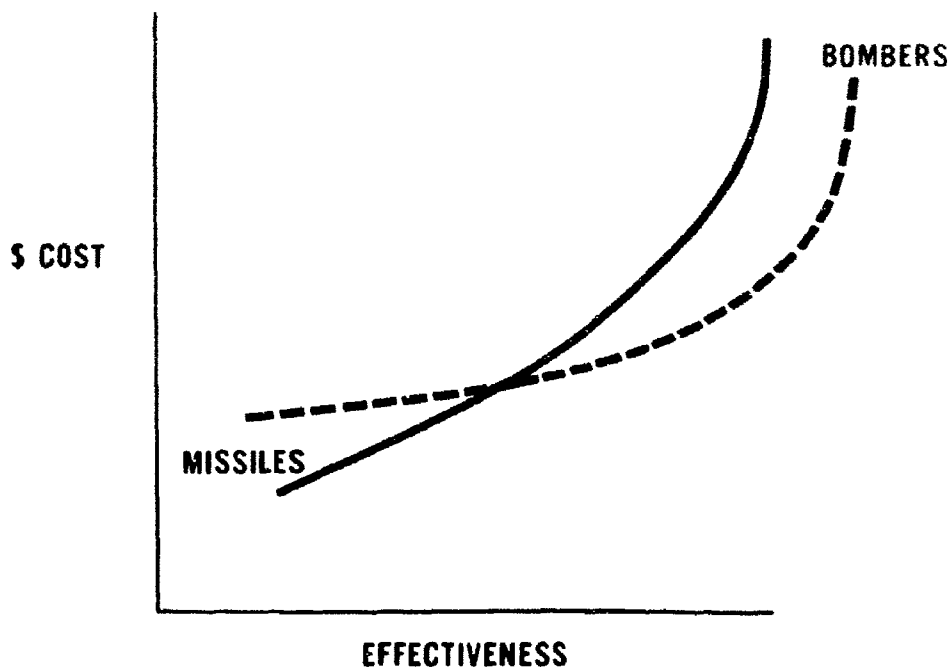


Fig. 27—Cost-Effectiveness Curves for Two Weapons Systems

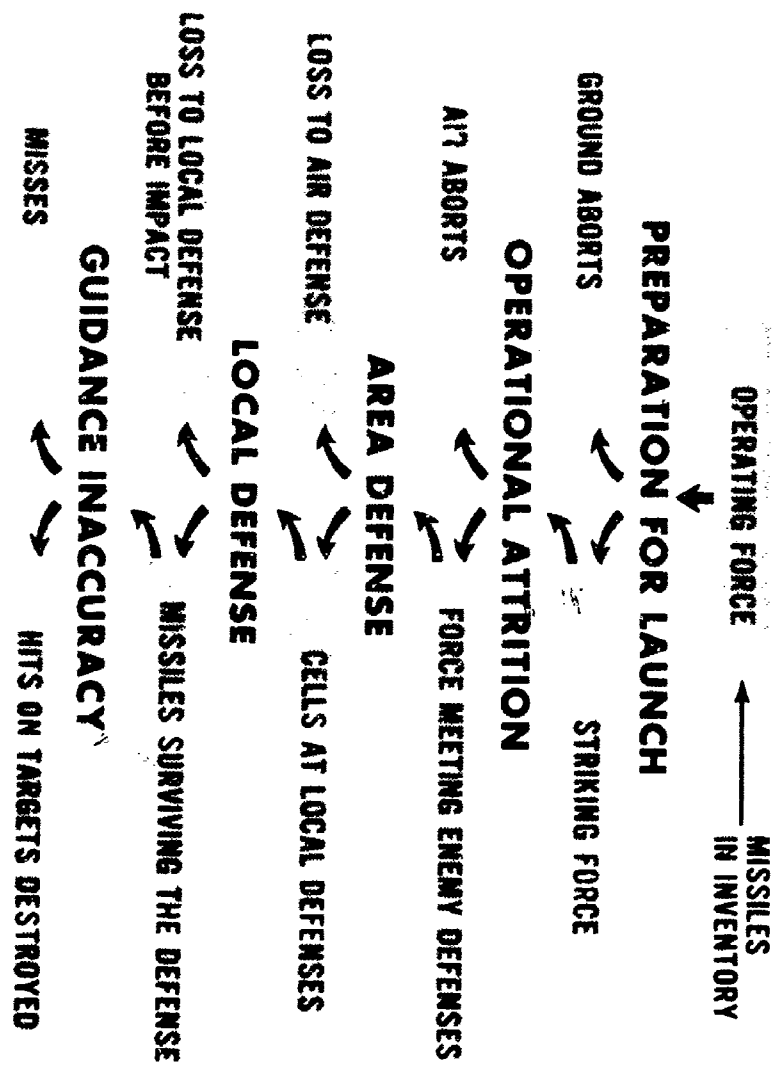


Fig. 28—Effectiveness Model for Strategic-Missile Strikes

The best that he could do here is to draw an envelope curve along the bottom which says, "This is the curve along which you want to be, and other things have to be taken into consideration at much higher levels to determine what level of cost or effectiveness is to be selected."

Let me shift from this rather academic drawing of curves to brief illustrations of the things called "models," the calculations that support cost-effectiveness studies.

Let me start with an example of an effectiveness model (Fig. 28). This is one for strategic-missile strikes. One can work this either up or down. If we do the analysis on the basis of a constant or an equal-effectiveness case and if we are concerned with minimizing cost, we start by specifying the number of targets destroyed and work our way up the chart to determine the size of the operating force and the number of missiles of a particular kind that have to be in the inventory, at which point we begin estimating the cost that would have to be met to have this number of missiles in the inventory.

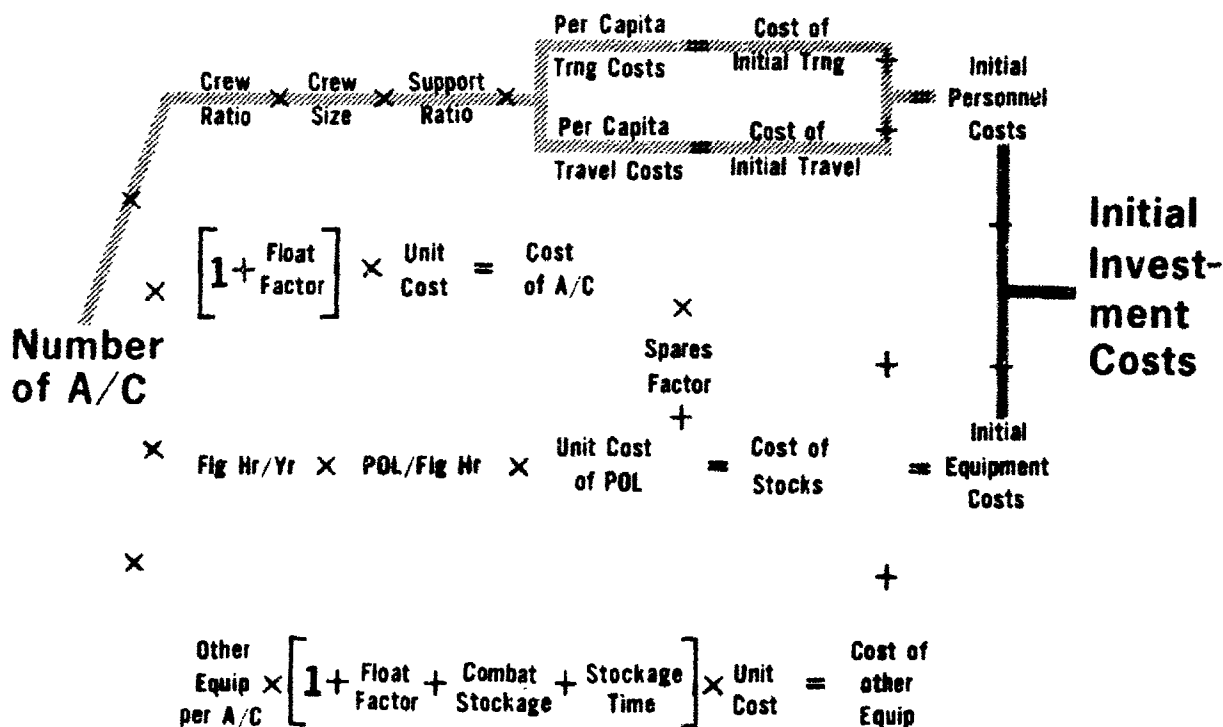


Fig. 29—Initial-Investment-Cost-Model Flow

Going the other way, downward with a fixed budget, one can begin with the number of dollars, estimate the number of missiles for each alternative that can be included in the inventory, work through the various losses that are to be expected, and end with the survivors and the number of targets destroyed.

This is one kind of effectiveness analysis. Again, I haven't gone into all the problems of how you make reasonable guesses or estimates as to each of

these things such as air aborts, losses to air defense, etc. It is an art in itself—scarcely a science—and cost-effectiveness analysis contains a very rich menu of things that need to be done, and done better. We are only identifying rather than exploring very carefully in this short paper.

Let me switch to give you the flavor of the cost side of the picture.

Let's take an actual cost model, or part of a cost model. This one deals with aircraft. Actually it was designed for a helicopter analysis. An effectiveness model gave us an inventory number of aircraft. We then wished to move from that into an estimate of the cost, in Fig. 29 initial cost. I don't want to bother to go through all this but merely to indicate the kinds of information needed to perform the cost analysis.

Not only financial information but also physical and program information—crew ratios, crew sizes, support ratios, float factors, POL per flying hour, stocking policy, and whatnot are needed.

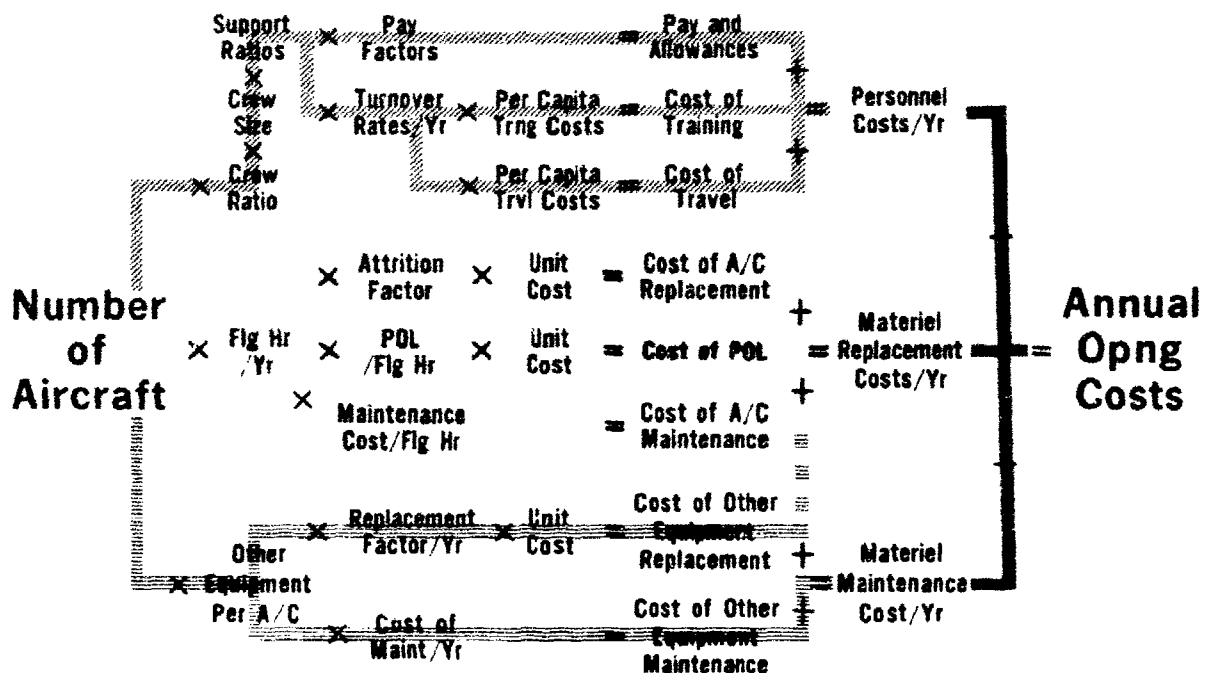


Fig. 30—Annual-Operating-Cost-Model Flow

As we move over into the operating side (Fig. 30) again the same classes of information are necessary. Both cost information and operational factors—attrition, turnover rates, replacement, and the like, are needed.

The difficulties of doing these things reasonably, making the estimates themselves, are numerous and large. In most of our offices and in most of the services, even though there is a long tradition of data collection and analysis that one can draw on, the development of useful, credible measurements for

these analyses is still largely ahead of us, and there are many people struggling with these problems.

What I have tried to do in this paper is to lay out a framework that relates objectives, costs, and alternatives, and to take you a little bit into the minds of people who are engaged in cost-effectiveness analysis, to give you some insight into the approaches that led to the kinds of questions, the kinds of formulations, and the kinds of measurements we make.