APPLIED SYSTEMS ANALYSIS

Engineering Planning and Technology Management

Richard de Neufville
Massachusetts Institute of Technology

McGraw-Hill Publishing Company
New York St. Louis San Francisco Auckland Bogotá Caracas Hamburg
Lisbon London Madrid Mexico Milan Montreal New Delhi Oklahoma City
Paris San Juan São Paulo Singapore Sydney Tokyo Toronto

12.9. *Hi-Tacky Corporation*
The Hi-Tacky Corporation is considering a new energy efficient heating system that will provide savings in current dollars of $5000/yr. Based on the following information:

- Taxes are paid at the rate of 50%.
- Inflation has an annual rate of 8%.
- The prime interest rate is 7%.
- After-tax return on other long-term investments is 12%.
- Savings certificates from the local bank pay 5%.

What discount rate should it use when evaluating the heating system?

12.10. *Start-Up*
Your friend the entrepreneur has just started a new business. Your advice is needed on the discount rate to be used to evaluate new opportunities. Looking through the financial records, you find that your friend could already

- insulate the building for $40,000, which would save 5600 gal/yr of fuel, currently valued at $1/gal.
- pay off $80,000 borrowed at a rate of 12% on the balance.
- pay $20,000 for an annuity paying $3200/yr for 30 years.
- lend to another entrepreneur who guarantees to double a $30,000 investment in 5 years.

Your friend has $60,000 in cash for investment. Estimating inflation at 4% a year, what is your friend's minimum discount rate for a $20,000 investment? a $60,000 investment?

12.11. *Government Procurement*
The local government has several options for its $200,000 project fund:
(i) Establish an in-house desk-top publishing office, to get annual savings estimated at $28,000 in today's money.
(ii) Exercise an option to buy the land under their parking area, on which they now have a 30-year lease at $38,000/yr.
(iii) Buy the computer equipment they now lease for $70,000/yr. This will have to be junked in 5 years.
Estimating inflation at 6% annually, rank the above projects.

CHAPTER 13

ECONOMIC EVALUATION

The purpose of an economic evaluation is to determine whether any project or investment is financially desirable. Specifically, an evaluation addresses two sorts of questions:

- Is any individual project worthwhile? That is, does it meet our minimum standards?
- Which is the best project in a list of possibilities? What is the ranking of projects on this list?

This chapter shows how both these questions should be answered.

Economic evaluations are difficult to do correctly in practice. This is in great part because this work is done by middle-level managers or staff who necessarily, by the fact that they see only part of their company's or agency's activities, cannot realistically take all the appropriate factors into account. The result is that most evaluations are done on the basis of assumptions often out-of-date or otherwise inaccurate for the situation at hand.

Conceptual difficulties are another source of error and confusion in economic evaluation. A number of the standard criteria for evaluation contain biases which make them inappropriate and even quite wrong for particular kinds of situations. This chapter focuses on these issues so that the practitioner will be able—to the extent possible within the requirements of employers or clients—to select the most suitable criteria of economic evaluation.

The core of this chapter is the presentation of the variety of possible criteria for evaluation, in Section 13.3. These include net present value, benefit-cost ratios, internal rate of return, cost-effectiveness ratio, and payback periods. Each method is discussed in detail and then compared to the others in Section 13.4. The chapter concludes with an application illustrating the way an economic evaluation can be done.

13.1 BASIC METHODOLOGY

The essence of all economic evaluation is a discounted cash flow analysis. The first step in every situation is to lay out the estimated cash flow, the sequence of benefits and costs over time. These cash flows are then discounted back to the present, using the methods shown in Chapter 11, either directly or indirectly in the case of the rate of return and payback period methods. The basic analysis can in all cases be simply done by the spreadsheet programs routinely available for personal computers.

The evaluation then assesses the merit of projects by comparing the discounted cash flows of benefits and costs. The project appears to be worthwhile if the benefits exceed the costs. The relative ranking of the projects is then determined by one of the several evaluation criteria—discussed in Section 13.3—that manipulate the discounted cash flow in various ways.

The methods of evaluation differ from each other principally in the way they handle the results of the discounted cash flow analysis. The present value method focuses on the difference between the discounted benefits and costs, the benefit cost and other ratio methods involve various comparisons of these qualities, and the rate of return method tries to equalize them. The question of what one does with the results of the discounted cash flows is the central problem of economic evaluation.

Most methods presume that the discount rate to be used in the cash flow analysis is known. This is often a reasonable assumption, since many companies or agencies require that a specific rate be used for all their economic evaluations. In many instances, however, the discount rate must be determined; this may be done as shown in Chapter 12.

It will be essential to remember, in carrying out an evaluation, that the correct selection of the discount rate may be crucial. The choice of the rate can easily change the ranking of projects, making one or another appear best depending on the rate used. This is because lower rates make long-term projects, with benefits in the distant future, appear much more attractive—relative to short-term projects with immediate benefits—than they would be if a higher rate were used (see Section 11.4). This phenomenon is discussed and illustrated in Section 13.3, which presents the different criteria of evaluation.

13.2 MINIMUM STANDARDS

Every evaluation deals with two distinct sets of projects or alternatives: the explicit and implicit possibilities. The explicit set consists of the opportunities that are to be considered in detail; they are the focus of the analysis. The implicit set, which can only be defined imprecisely, is important because it provides the terms of reference for the evaluation and defines the minimum standards.

Explicit set of alternatives. This is a limited list of the potential projects that could actually be chosen. The list is usually defined by some manager concerned with a particular topic, for example:

- An official of the department of highways, responsible for maintenance and construction of roads
- A manager of a computer center, proposing to acquire new equipment
- An investment officer for a bank, presenting a menu of opportunities for loans to construction projects

The lists of projects suggested by each of the preceding situations illustrate two characteristics typical of the explicit choices considered by an evaluation. The explicit set is

- limited in scope, in that it only includes a portion of the projects in front of the organization as a whole. Thus the manager of the computer center is only competent in, and only considers various ways to improve the information systems; whether money should be spent on developing a new product or replacing the central heating is literally not his or her department.
- limited in number, being only a fraction of all the projects that could be defined over the next several years. Usually, the explicit list deals only with the immediate choices, not the ones that could occur during the next budget or decision period.

The fact that the sets of projects we consider explicitly are limited poses a basic problem for any organization. The difficulty is that any procedure that analyzes separate sets of projects independently can quite easily lead to a list of recommended choices that are not the best ones for the group. By optimizing for each subset of the entire range of alternatives that exist over time, over the departments of an organization, and over its regions, we are likely to suboptimize for the organization as a whole. For example, consider a company with a computer department, a research laboratory, and a producing plant: if we evaluate the projects proposed by each group we can determine the best computer, the best instrument, and the best machine tool to buy. But this plan may not be in the best interests of the company; it is quite possible that the second best machine tool is a better investment than the best instrument, or that none of the computers is worthwhile financially.

The issue is: How does an organization insure that the projects selected by its components are best for the organization as a whole? In addressing this question we must recognize that the obvious answer, of considering all possible projects simultaneously, is neither practical nor even possible. A large number of analyses could be done, but the level of computation is not the real obstacle.

An analysis of all alternatives at once is not practical because it would be extremely difficult for any group in an organization to be sufficiently knowledgeable both to generate the possible projects for all departments, and to estimate their benefits and costs; they simply would not have sufficient knowledge of the topic, region, or clients. Further, the analysis of all alternatives at once is not even conceptually feasible because we are unable to predict what options will be available in the future. We can therefore never be sure that the projects we select from a current list, however comprehensive it may be, will include all the opportunities that will occur over the life of the projects, and that might otherwise be selected. Some degree of suboptimization cannot be avoided.

To lessen the possibility for suboptimization it is necessary to create some means to make the evaluation of any set of explicit alternatives less dependent on other evaluations. This can be done by creating a substitute for the whole list of innumerable possible alternatives. This is the role of the implicit alternatives.

Implicit set of alternatives. This set generally represents all the projects that have been available previously and that might be available in the reasonable future. Since it refers in part to unknown prospects, it can never be described in detail. It thus indicates, with inherent imprecision, what could be done instead of the immediate, explicit alternatives.

The implicit set of alternatives is of interest because it establishes the minimum standards for deciding if any explicit project is worthwhile. To illustrate this, consider the situation in which a person has been making investments and has consistently been able to choose possibilities that provide yearly profits of 12% or more, and has rejected all others with lesser returns. Faced now with the problem of evaluating an explicit set of specific proposals, this person will naturally turn to past experience for guidance. If the investment possibilities have not fundamentally changed, the person may assume that there are continued possibilities—the implicit set of alternatives—for earning 12% or more as before and should correctly conclude that any explicit choice can only be worthwhile if its profitability equals or exceeds the 12% implicitly available elsewhere.

The minimum standards suggested by the implicit alternatives can be stated in several ways. An obvious and common way is to stipulate a minimum acceptable annual rate of return. Minimum standards of profitability can also be expressed quite differently, however. In business, they are typically stated in terms of the highest number of periods that will be required for the benefits to equal the initial investment (the maximum payback period, see Section 13.3). Minimum standards can also be defined in terms of minimum ratios of benefits to costs.

Organizations use minimum standards for the economic acceptability of projects as the way to reduce the possibility of suboptimization. These standards force each separate department or group to take into account the other opportunities available to the organization: they cannot, for example, choose projects unless they are at least as good as others available elsewhere to the organization.

13.3 EVALUATION CRITERIA

This section defines the several criteria for economic desirability used in evaluation. These fall naturally into two groups. The first consist of a variety of ways of using the discounted cash flow of benefits and of costs associated with any

project. These are the net present value, the benefit-cost ratios, and the internal rate of return. The second group includes two variants that provide a way around some of the operational difficulties associated with the other criteria: these are the cost-effectiveness ratio and the payback period.

The definition of each method is followed by a discussion of its major advantages, disadvantages, and uses. The next section, 13.4, summarizes this information for reference. Throughout this discussion, all references to benefits, B, and costs, C, are taken to be given in present values as calculated by the formulas of Section 11.3.

Net present value. The net present value of a project (NPV) is simply the difference between the discounted benefits, B, and costs, C, associated with the project:

$$\text{NPV} = B - C$$

Naturally, analysts should maximize NPV. In practice, projects would be ranked by this quantity.

Some academics assert that the net present value criterion should be used in all economic analyses. This prescription should be resisted. NPV only provides a good comparison between projects when they are strictly comparable in terms of level of investment or total budget. This condition is rarely met in the real world, as indicated below. The practical consequence is that net present values are primarily used for the analysis of investments, particularly of specific sums of money, rather than for the evaluation of projects, which come in many different sizes.

The advantage of the net present value criterion is that it focuses attention on quantity of money, which is what the evaluation is ultimately concerned with. NPV differs in this respect from the other criteria of evaluation, which rank projects by ratios and which thus do not directly address the bottom line question of maximizing profit.

One disadvantage of NPV is that its precise meaning is difficult to explain; practical-minded people such as businesspersons thus tend to avoid the concept. NPV suggests profit, but in fact is not profit in any usual sense of the term. In ordinary language, profit is the difference between what we receive and what we pay out. As an example, consider an investment now for a lump sum of revenue later. This is, crudely,

$$\text{Profit} = \text{Money Received} - \text{Money Invested}$$

More precisely, if we had to borrow money to make the original investment, the profit would be net of interest paid:

$$\text{Profit} = \text{Money Received} - (\text{Money Invested})(1 + i)^N$$

where i is the interest rate. This profit can also be placed in present value terms, using the appropriate discount rate for the group concerned:

$$\text{Present value of profit} = (\text{Money Received})(1 + r)^{-N} - (\text{Money Invested})(1 + i)^N(1 + r)^{-N}$$

The important aspect to notice is that

$$\text{NPV} \neq \text{Present value of profit}$$

This is because the discount rate is not, in general, equal to the interest rate. As Chapter 12 indicates, the discount rate already reflects some degree of profitability. Thus, even when the net present value equals zero, the project may be profitable, as understood in common language. A project with NPV = 0 is simply not advantageous as compared to other alternatives the group has. Net Present Value thus indicates "extra profitability" beyond the minimum. As a reader, you probably found it difficult to grasp this subtlety; this demonstrates the point that NPV is a difficult measure to use.

Another difficulty with the net present value criterion is that it gives no indication of the scale of effort required to achieve the result. To see this, consider the problem of evaluating the two projects defined in Table 13.1. If one considers only net value, Project S appears best. Most investors would consider that an absurd choice, however, because of the difference in scale between the projects. Taking scale into account, T presumably gives a much better return than S: the money saved by investing in T rather than S can be invested either in other explicit projects or ones that will eventually be available and that will offer more net present value than S. In any case, net present value by itself is not a good criterion for ranking projects.

Formally, the essential conditions for net present value to be an appropriate criterion of the evaluation and ranking of projects are that

- we have a fixed budget to invest.
- projects require the same investment.

These conditions rarely hold. On the contrary, it is most generally the case that the list of projects consists of a variety of possibilities of different costs. Often a central problem in the evaluation and choice of systems is to define which size of system to build and how much to spend. Analysis of net present value is not particularly helpful in those contexts.

Benefit-cost (or cost-benefit) ratio. The benefit-cost ratio is the quotient of the monetary value of benefits of a project divided by its costs:

$$\text{Benefit/Cost} = B/C$$

TABLE 13.1
Evaluation of projects S and T, illustrating how net present value criterion masks scale of effort required

Project	Benefit ($)	Cost ($)	Net value ($)	NPV as % of cost
S	2,002,000	2,000,000	2000	0.1
T	2000	1000	1000	100

It is nondimensional by definition. The presumption is that projects with a benefit-cost greater than 1.0 are desirable, because benefits exceed costs. It is also assumed that projects with higher benefit-cost ratios are more desirable.

> **Semantic caution:** Professionals sometimes refer to cost-benefit analysis when evaluating projects using benefit-cost ratios. This analysis is exactly the same, the only perceptible difference is in language. Cost-benefit analysis is the term used in Britain, many countries of the British Commonwealth, and thus sometimes in international organizations. For particular definitions of benefits that attach value to benefits different from economic prices (see Section 21.3), the British also refer to Social Cost-Benefit Analysis.

The benefit-cost ratio is principally used in the evaluation of large-scale public projects. For these kinds of investments it is clearly the evaluation criterion preferred by many professionals. However, because this criterion has an inherent bias toward projects requiring heavy capital investments and against projects with high recurring costs due to sales or operations, as explained in what follows, the benefit-cost is not used by groups responsible for these kinds of projects. Benefit-cost ratios are thus typically associated with government proposals to build dams and canals in the United States, and airports and public transport railroads in Britain. Benefit-cost analysis is avoided by agencies dealing with irrigation, healthcare, education, or similar activities with recurring annual costs, and is apparently never used by business.

The advantages of the benefit-cost ratio are that

- it compares projects on a common scale.
- it directly provides an indication of whether a project is worthwhile (does the ratio exceed 1.0?).
- it provides an easy means to rank projects in order of relative merit.

The benefit-cost ratio is, therefore, much more useful in practice than NPV, since it permits us to deal easily with projects of different size.

Conversely, however, an immediate disadvantage of this criterion is that it requires that all benefits be assigned a monetary value. For a typical flood control project in the United States, for example, the benefit-cost evaluation requires prices for such items as human life and days of aquatic recreation, prices that are highly speculative at best. Benefit-cost analyses consequently give little weight to, and are biased against, objectives that are desirable but not easily measured by economics such as education, health, and environmental quality.

The major analytic weakness of the benefit-cost ratio lies with the ambiguity of the treatment of recurring costs and the consequent bias in favor of capital-intensive projects. As indicated in Sections 12.2 and 11.7, any project involves two quite different kinds of costs, which can be broadly classified as either capital or recurring. The capital costs, C_k, are the immediate, generally quite sizeable, investments. They are characteristically recuperated gradually over the life of the project, which may easily be many years and even up to 20 or more for public works. The recurring costs, C_r, on the other hand, are relatively small at any time and are spread out fairly smoothly over the life of the project. They consist of continuous costs of operation, maintenance, and administration of a project. They are typically paid out of current revenues. The essential difference between capital and recurring costs is thus their distribution over time and their relationship to the stream of benefits of a project. Figure 13.1 illustrates the situation.

The ambiguity for calculating the benefit-cost ratios arises in the following way. The normal rule for calculating benefit-cost ratios is to compare benefits to *all* costs:

$$\frac{\text{All Benefits}}{\text{All Costs}} = \frac{B}{(C_k + C_r)}$$

Alternatively, however, one can argue that costs repaid almost immediately are not really costs to the project and are not really relevant to the ultimate issue, which is whether the net revenues or benefits from any period justify the initial investment. In this second case the appropriate criterion is

$$\frac{\text{Net Benefits}}{\text{Investment}} = \frac{(B - C_r)}{C_k}$$

These two benefit-cost ratios are far from equivalent. The Net Benefit ratio is necessarily greater:

$$\frac{\text{Net Benefit}}{\text{Cost}} > \frac{\text{Benefit}}{\text{All Cost}}$$

It can easily be the case that a project that appears undesirable when total benefits are compared to costs is actually quite profitable when the focus is on net benefits (see box). Businesses, which typically have high costs of sales each year, are quite aware of this fact and never use benefit-cost ratios.

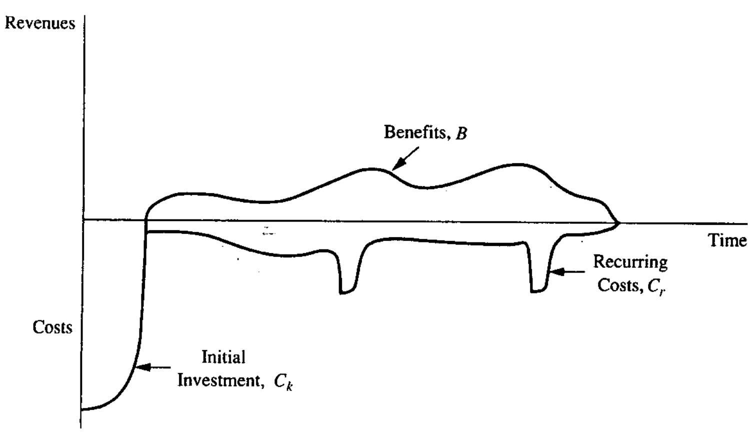

FIGURE 13.1
The relationship of benefits to capital and recurring costs.

Bias of Benefit-Cost Analysis Toward Capital Projects

Consider the two projects shown in Table 13.2, both with the same initial investment of C_k = \$1,000,000, and having a useful life of 10 years. They differ as to the stream of benefits and costs over time. Figuring all benefits and costs on a present value basis, Project K has low recurring costs of only \$50,000 per year, with annual benefits of \$200,000. It is representative of capital-intensive projects such as hydroelectric facilities, communications satellites, and so on. Project R, however, has high annual costs of \$500,000 as well as big annual benefits of \$700,000. It is typical of the large class of projects with high recurring costs either due to operations, such as irrigation of crops by pumping, or due to the rapid turnover of stock, as in a supermarket or retail stores more generally.

For an accountant looking at the results each year, the meaningful difference is that Project R earns \$50,000 more annually, and ends up netting twice as much as Project K. On that basis Project R is clearly to be preferred. But the benefit-cost analysis would have us prefer Project K to R as indicated in the table!

The fact is that the benefit-cost ratio counts the recurring costs, which are covered immediately by the benefits, on the same basis as the capital investment, which is sunk for a long time. This leads to a bias against projects with high recurring costs and toward those with large investments. This is why the benefit-cost ratio is favored by agencies interested in capital-intensive public works.

TABLE 13.2
A comparison of a capital intensive and operations project (all costs and benefits in present values)

Project	K		R
Investment, C_k	\$1,000,000		\$1,000,000
Annual costs, C_r	\$ 50,000		\$ 500,000
Annual benefits	\$ 200,000		\$ 700,000
Annual net return	\$ 150,000		\$ 200,000
Useful life	10 Years		10 Years
Total benefits	\$2,000,000		\$7,000,000
Total costs, $C_k + C_r$	\$1,500,000		\$6,000,000
Benefit/cost ratio	1.34	better than	1.17
Annual return	15%	worse than	20%
Net present value	\$ 500,000	worse than	\$1,000,000

There is no satisfactory way around the bias of the benefit-cost ratio against projects with high operating costs. This is because the broad classification of costs into two types is not sufficiently precise for any real situation. Since projects rapidly appear more desirable as more costs are subtracted from the divisor, there would be great temptation to manipulate the ratio. It would thus be difficult to be confident in the meaning and comparability of benefit-cost ratios computed on the basis of net benefits. Government agencies and other users of benefit-cost ratios have thus strenuously resisted attempts to use any ratio other than that of benefits to total costs.

The bias of the benefit-cost ratio against projects with high operating costs is a main reason why many specialists recommend the use of the net present value criterion. The difficulties with that criterion, however, do not make the choice clear.

Another disadvantage of the benefit-cost criterion is that the relative rank it gives to projects depends on the discount rate used. This is because, as indicated in Section 11.5, lower discount rates favor projects with longer-term benefits. Thus these can appear better than projects with benefits accruing sooner if a lower rate is used in the analysis. Table 13.3 illustrates this phenomenon: Project A, with the more immediate benefits, appears better than Project B for a discount rate of 10%; the ranking is reversed for a discount rate of 3%. This again underlines the importance of selecting the proper discount rate.

Internal rate of return. The internal rate of return (IRR) is the discount rate for which the net present value of a project is zero. That is,

$$\text{Internal Rate of Return} = r_{irr}$$

such that

$$\text{NPV (project)} = 0$$

The concept is that the internal rate of return indicates the real return of any project, what we called r_p in Section 12.3. It is a precise way of expressing the common notion of "return on investment." For evaluation, the idea is that projects should thus be ranked from the highest internal rate of return on down.

TABLE 13.3
Example of how ranking of projects by benefit-cost criterion can depend on discount rate used

Project	Investment C_k (\$)	Annual benefit R (\$)	Project life N years	Benefit-cost at discount rate of 3%	Benefit-cost at discount rate of 10%
A	1000	200	10	1.71	*1.23 (best)*
B	1000	125	20	*1.86 (best)*	1.06

The internal rate of return is now increasingly used by sophisticated analysts in business. For many, however, the complexity of its use has overwhelmed its conceptual advantage. As the internal rate of return becomes easier to calculate with the wider use of personal computers, it may be more widely used.

The advantage of the internal rate of return criterion is that it overcomes two difficulties inherent in the calculation of both net present value and of benefit-cost ratios. These are that

- it eliminates the need to determine, indeed to argue about, the appropriate discount rate.
- its rankings cannot be manipulated by the choice of a discount rate.

It also focuses attention directly on the rate of return of each project, a feature that cannot be understood from either the net present value or the benefit-cost ratio.

The obvious disadvantage of the internal rate of return criterion is that it is generally difficult to calculate. A direct solution for the internal rate of return is available only for projects with a stream of constant benefits, R, over a period: The internal rate of return can then be found from handbook tables as the discount rate for which the capital recovery factor equals R/C_k. Usually, the internal rate of return must be found by trial and error (see box). These calculations have been a real burden in the past, but can now be done relatively easily with standard spreadsheet programs available on personal computers.

Calculation of Internal Rate of Return by Trial and Error

To find the internal rate of return, we first pick two trial discount rates to calculate the net present value of a project. From these answers we guess the approximate location of the IRR, and calculate a new net present value. This procedure goes on until the answer is obtained to the accuracy desired. This can be done automatically by a spreadsheet program of a personal computer.

Consider the project Q in Table 13.4. First try discount rates of 10 and 20%:

$$r = 10\% \rightarrow \text{NPV} = +4.09$$

$$r = 20\% \rightarrow \text{NPV} = -4.76$$

The internal rate of return seems to lie in between. Try

$$r = 15\% \rightarrow \text{NPV} = +1.19$$

The internal rate of return is thus somewhat larger. Try

$$r = 16\% \rightarrow \text{NPV} = +0.19$$

The actual solution for internal rate of return here, to the author's satisfaction, is:

$$\text{IRR} = 16.18\%$$

TABLE 13.4
Examples of projects that can lead to ambiguous solutions for the internal rate of return

Project	Investment ($)	Annual benefit ($)	Project life (years)	Closure cost, year $N + 1$ ($)
P	C_k	R	N	$C_c > RN - C_k$
Q	200	100	5	310

Another disadvantage of the internal rate of return criterion is that it can be ambiguous. The solution of the condition that NPV = 0 can lead to two or more solutions; one then really cannot tell what the internal rate of return is. This ambiguity can occur whenever a project involve some final costs of closing the project, C_c. These could occur through the requirement to clean up a site on completion, as required in the United States for strip mines, to pay pensions or severance pay to workers, or to settle claims. The ambiguity can arise whenever the closure costs exceed the total undiscounted benefits less the investment:

$$\text{Condition for Possible Ambiguity: } C_c > RN - C_k$$

In this situation, shown in Table 13.4, the net present value is clearly negative for two discount rates:

$$r = 0 \rightarrow \text{NPV} = RN - C_k - C_c < 0$$
$$r = \infty \rightarrow \text{NPV} = -C_k < 0$$

If there is any discount rate for which NPV is positive, there must be two solutions that make NPV = 0 (see box and Figure 13.2).

Finally, the internal rate of return also leads to different rankings than those produced by the benefit-cost ratio. Table 13.5 makes the point.

Example of Ambiguity in Calculation of Internal Rate of Return

Consider Project Q in Table 13.4. One solution (see previous box) is

$$\text{IRR}_1 = 16.18\%$$

The other is lower since for a zero discount rate the net present value is negative. Thus

$$r = 0\% \rightarrow \text{NPV} = -10$$

The second solution is in fact:

$$\text{IRR}_2 = 3.89\%$$

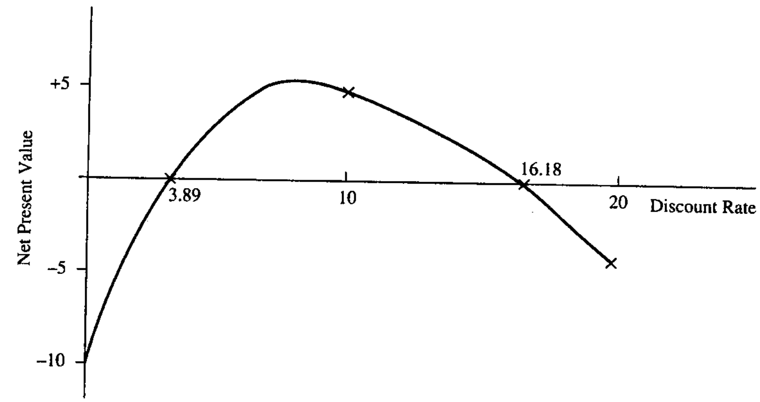

FIGURE 13.2
Net present value as a function of discount rate for Project Q, illustrating its ambiguous values of 3.89% and 16.18% for the internal rate of return.

Cost-effectiveness ratio. The cost-effectiveness ratio is similar to the benefit-cost ratio. The main conceptual difference is that benefits are measured by their physical quantity rather than in monetary units. This quantity is considered the effectiveness of a project. The ratio is thus

$$\text{Cost-Effectiveness} = \frac{\text{(Units of Benefit)}}{\text{Cost}}$$

For example, one might evaluate safety projects in terms of "lives saved from accident per thousand dollars." Naturally, we wish to maximize cost-effectiveness.

It is sometimes useful to invert the cost-effectiveness ratio, so that one has the average cost per unit of effectiveness. This can be useful when one tries to estimate suitable prices for services.

Cost-effectiveness is widely used in government agencies, particularly those that produce services that do not have a market price, or for which it seems

TABLE 13.5
Example of how ranking of projects by internal rate of return and benefit-cost ratio can differ

Project	Investment C_k ($)	Annual benefit R ($)	Project life N years	Benefit-cost $r = 3\%$	Internal rate of return (%)
A	1000	200	10	1.71	*15.10 (best)*
B	1000	125	20	*1.86 (best)*	10.93

unsuitable to charge a price. These services include public goods such as environmental protection, defense, public health, and police. The criterion is only suitable when the benefits do not have a monetary value: it would be appropriate for the Environmental Protection Agency to do a cost-effectiveness analysis to find the best way to reduce a carcinogenic pollutant, but not to evaluate a new heating system that would reduce the energy bills of its headquarters.

The principal peculiar advantage of the cost-effectiveness ratio is indeed that it avoids the awkward issue of trying to assign monetary values to benefits such as "lives saved." These estimates are extremely controversial both as regards the actual value and the ethical basis. There are, for example, many ways used in practice to value life; the courts, for example, do this routinely when awarding death benefits. These amounts vary widely, however, and there is no good average value. Furthermore, there is also considerable argument about the proper ethical basis for assigning a price to life: should all life be valued equally? or should the family be compensated more for the loss of the breadwinner than for a dependent grandparent? Any monetary value assigned to such benefits is therefore not likely to be widely acceptable, so that neither is a benefit-cost analysis based on such figures. It is therefore preferable, for these cases, to sidestep this difficulty and to focus on getting the greatest benefit for the public's money. This is an objective that all can support.

Our analysis of the primary water supply system for New York City provides a good example of the use of cost-effectiveness analysis. In this case, a main objective of the investment in City Tunnel Number 3 was to raise the minimum pressure of the water as delivered. Designs with different diameters and layouts were more or less effective as shown by Figure 13.3 (a reproduction of Figure 4.10). In this case we were able to indicate that the original design was not particularly cost-effective, and that much more value for money could be obtained with a less expensive design using a smaller diameter. This is the project that was chosen.

A major disadvantage of the cost-effectiveness ratio is that it does not define any minimum standard. Since it does not place effectiveness on the same scale as cost, it provides no way to know whether the improvements offered by a project are worthwhile in all. Thus in Figure 13.3, we can identify the best design for a project if we are going to do it, but cannot use the analysis to justify the project itself. What if there is no need for the "benefit" provided by the project and if it is therefore essentially worthless?

Payback period. The payback period is the number of periods, usually measured in years, it takes for the net *undiscounted* benefits of each period to equal (to pay back) the initial investment. The method assumes that these benefits are equal in each future year. The formula is then:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Net Undiscounted Benefits}}$$

The concept of the payback period is distinct from the other evaluation criteria in that it explicitly recognizes some of the time aspects of a project.

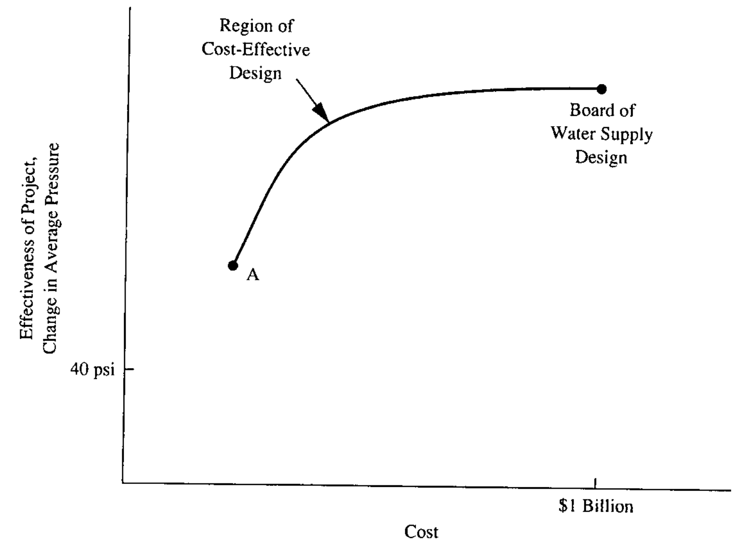

FIGURE 13.3
Cost-effectiveness curve for the Third City Water Tunnel for New York City, the envelope of best performance for the cost of hundreds of designs simulated by computer. The most cost-effective designs are at the knee of the curve.

The nature of the payback period can be appreciated by considering its formula in detail. Given that a project provides an annual net benefit of R each period for N periods, the payback period is

$$\text{Payback Period} = \frac{C_k}{R}$$

This can be restated in terms of a benefit-cost ratio by recalling (see Section 11.3) that

$$\text{Present Value of Benefits} = \frac{R}{\text{(Capital Recovery Factor)}}$$

We then have

$$\text{Payback Period} = \left[\frac{\text{Benefit}}{\text{Cost}}\right]^{-1} \text{(Capital Recovery Factor)}^{-1}$$

That is, the payback period varies inversely with the benefit-cost ratio: the shorter the payback period, the higher the benefit-cost.

The relationship between the payback period and the benefit-cost ratio is more obvious when we consider the limiting case for long term projects for which the capital recovery factor approximately equals r (see Section 11.3). Then

$$\left[\frac{\text{Benefit}}{\text{Cost}}\right] = [r(\text{Payback Period})]^{-1}$$

As a project will only be acceptable if [Benefit/Cost] ≥ 1.0, the minimally acceptable payback period must be smaller than $1/r$. Thus for a discount rate of 20%, the minimum payback period is less than five years. In practice, companies often insist on payback periods of as little as two to three years.

The great advantage of the payback period is that it is simple and can be applied by anyone. It is thus an excellent mechanism for allowing middle managers and technical staff to choose among proposals without going through a detailed analysis, or to sort through many possibilities before using another criterion.

Situations suitable for the use of the payback period are often found in industry. These are projects in which some constant benefit is expected to accrue for an extended period as a result of a particular investment. A typical case would be the purchase of a new machine that would save some quantity of operating expenses each year, or some insulation or control that would regularly save on energy costs.

The disadvantage of the payback period criterion is that it is crude; it does not clearly distinguish between projects with different useful lives. For any projects with identical useful lives, for which the capital recovery factor will be identical, the payback period gives as good a measure of economic desirability as the benefit-cost ratio. When the useful lives of projects are different, the capital recovery factors are not identical and the payback period criterion can give a poor indication of the desirability of a project.

Table 13.6 provides an example of this. Project V has a shorter payback period than Project W, and would appear better by this criterion. Yet Project W is in fact more economically desirable for a wide range of discount rates. This is because W provides substantial benefits over a much longer period. Thus over a six year cycle, Project V would have to be repeated twice for a total cost of \$4000 and benefits of \$6000, whereas Project W would only cost \$2000 and yield benefits of \$4800, greater net benefits and a higher benefit-cost ratio for a range of suitable discount rates.

TABLE 13.6
Evaluation of Projects V and W, illustrating limitation of payback criterion

Project	Investment C_k (\$)	Benefits by year (\$) 1	2	3	4	5	6	Payback period, years	NPV at 10%	IRR (%)
V	2000	1000	1000	1000				2	487	23.4
W	2000	800	800	800	800	800	800	2.5	1484	32.7

13.4 COMPARISON OF CRITERIA

Table 13.7 summarizes the major features of the criteria of economic evaluation. The essential message is that no one criterion is best for all purposes. Each has its own place and role.

Businesses will generally use the internal rate of return or payback period criteria, depending on who they have doing the analysis. Senior managers and others examining major investments for the company should use the internal rate of return for its precision, despite its difficulties. Middle managers and technical staff primarily responsible for operations will find the payback criterion most effective, given its simplicity and the fact that its inaccuracy as a method may be no worse than the inaccuracy of the data.

Government agencies and international development organizations will prefer to use the benefit-cost ratio for evaluating major capital-intensive and public works. For them the general ranking of projects is an important consideration. The fact that this criterion is not perfect theoretically, since it has a bias toward capital-intensive projects and does not indicate scale, is not especially significant in a political environment, where many decisions are made for noneconomic reasons and it is mostly important to make choices that are financially worthwhile, if not optimal.

Government agencies responsible for the delivery of services which effectively do not have market prices—such as defense, fire protection, public health, and education—should use cost-effectiveness analyses to evaluate alternatives for improving these services. Because attempts to assign monetary values to such items as lives saved, cancers avoided, and years of education are so controversial—both regarding the numbers and on fundamental ethical grounds—it is most reasonable to avoid such issues. Cost-effectiveness analysis serves this purpose well.

Academics, particularly those who have not had to deal with real problems, tend to prefer the net present value criterion for its theoretical clarity. In practice, it is difficult both to apply to the important task of ranking projects of different size, and to explain to others. Surveys of business and government practice indicate that neither group ever really uses this criterion.

The differences between the net present value, benefit-cost ratio, and the internal rate of return can be illustrated graphically. Consider a situation in which we have to decide on the size of a project, for example, the height of a hydroelectric dam or the production capacity of a factory. For any given level of investment, C_k, and discount rate, r, we can calculate the net present value of the project. Each solid line in Figure 13.4 shows a possible locus of these answers for a project for which there are sizable initial fixed costs, followed by decreasing marginal returns. This graph permits us to see how the different evaluation criteria can lead to a different conclusion about the optimal size of the project.

The optimal size according to the net present value criterion using the discount rate r, is A, since this investment maximizes net present value. The optimal size according to the benefit-cost ratio is B, however, since this design

TABLE 13.7
Summary comparison of criteria for economic evaluation

Criterion	Characteristics				Advantages	Disadvantages
	Reflects scale	Ranks easily	Non $ benefits	Ease of use		
Net Present Value, NPV	NO	NO	NO	OK	Focus on value	Not Good for Ranking, Difficult Concept
Benefit/ Cost, *B/C*	YES	YES	NO	OK	Ranks Easily	Bias vs. Operations
Internal Rate of Return, IRR	NO	YES	NO	LOW	Approximates Rate of Return	Ambiguous Solutions
Cost/ Effectiveness, *C/E*	YES	YES	YES	GOOD	Handles Non-monetary Benefits	Projects May Not Compare
Payback Period	YES	YES	NO	HIGH	Simplicity	Inaccuracy

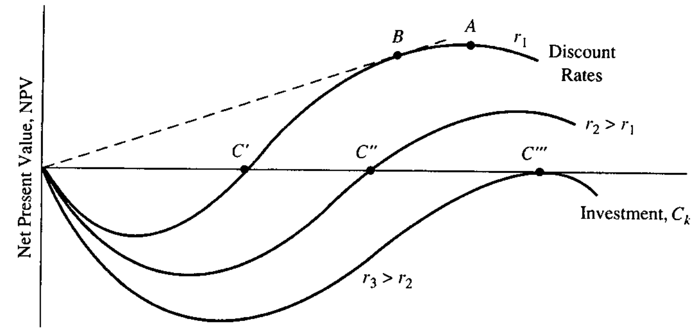

FIGURE 13.4
Illustration for showing how net present value, benefit-cost, and internal rate of return criteria lead to different prescriptions (see text).

maximizes that ratio. The solution obtained by the use of the internal rate of return is quite different: there is a different IRR for a wide range of sizes of projects, as indicated by C' and C'', and the project with the highest internal rate of return will be farthest to the right, at C'''.

13.5 RECOMMENDED PROCEDURE

How should the analyst proceed? Given the many criteria available, which should be used? The question appears complex but generally is not difficult to answer.

The first issue to resolve, in any situation, is whether the analyst really has a choice. Frequently there is no freedom: the client, agency or company has a set way of evaluating projects. In those majority of cases, the analyst will simply have to make the most of the established criterion.

How should the analyst cope when the standard evaluation criterion used by the client is inappropriate? The responsible approach is to explain carefully, as an addition to the evaluation, why the client should make adjustments in this particular case. For example, suppose a company is using the payback period criterion to evaluate machines with quite different lives: as illustrated by Table 13.6, this approach can be quite misleading. The way the author would cope with this situation is (1) to carry out the payback period analysis so that the company's managers would have an immediate point of comparison in their usual form, (2) to point out the perversity of the criterion in this specific case, so as (3) to end up with an alternative analysis that, exceptionally, seems more suitable.

When the organization routinely uses a couple of different criteria, the choice should be made according to two rules:

- Match the effort involved in the analysis with the importance of the issue.
- Use the method most suited to the peculiar nature of the problem.

The first rule leads companies to choose the payback criterion for "small" projects (which can be as large as $10 million) and the more complicated internal rate of return for larger projects. The second rule is that one should use cost-effectiveness analysis if the benefits are not monetary and, as indicated in Chapter 10 (particularly Section 10.4), decision analysis when there is considerable risk involved.

REFERENCES

Au, T., and Au, T. P., (1983). "Benefit-Cost Ratio Method," Chapter 7, and "Internal Rate of Return Method," Chapter 8, *Engineering Economics for Capital Investment Analysis*, Allyn and Bacon, Boston.

ATT Company, (1977). "Mathematics of Money," Chapter 5, and "Inflation and the Cost of Money," Chapter 10, *Engineering Economy*, 3rd ed., McGraw-Hill, New York.

PROBLEMS

13.1. *New Product Line*
An entrepreneur is considering three possibilities for investment but only has the time and management resources to do one. The initial investment and benefits of each choice are given below. Each investment is expected to last eight years.

	Financial aspects of product ($ × 10^3)		
	A	**B**	**C**
Initial investment	35	50	90
Annual net benefits	10	13	20
Liquidation value at end	0	2	5

(*a*) Rank the choices by net present value and benefit-cost ratio using an 8% discount rate, and by internal rate of return.
(*b*) Which product should be chosen?

13.2. *Envelope Machines*
The Eastern Stationery Co. has narrowed its choice to two alternatives for a new machine that makes envelopes from precut pieces of paper. The Ace Envelope Machine costs $20,000 and has an expected useful life of seven years. The Acme Heavy-Duty Envelope Former costs $26,000 and has an expected life span of ten years. Both machines have operating and maintenance costs of $9000 per year, can handle Eastern's demand, which is stable, and should have scrap values of $1000 at the end of their lives.
(*a*) It is clear that the Ace machine is the less expensive one of the two choices. Should Eastern buy it?
(*b*) What method of evaluation would you recommend?
(*c*) Using a discount rate of 12%, determine which machine Eastern should purchase.

13.3. *Energy-Saving Devices*
The owner of a small business wants to buy one of three energy-saving devices for his store. The costs and benefits are given in the following table. Each device has a five-year life.

	Financial aspects of device ($ × 10^3)		
	A	**B**	**C**
Device cost	2000	3000	3500
Annual energy savings	600	875	900
Salvage value	0	0	500

(*a*) Rank the devices by payback period, net present value, and benefit-cost ratio using a 10% discount rate.
(*b*) Rank them by payback period, net present value, and benefit-cost ratio using a 12% discount rate.
(*c*) Which device is better? Discuss and defend your choice.
(*d*) Sketch net present value vs. discount rate for devices A and B on a single graph by plotting NPV at 0, 10, 12, and 15%.
(*e*) Indicate on the graph the range of discount rates for which device A would be favored to B, and for which B would be favored to A.
(*f*) Discuss the importance of selecting a discount rate.

13.4. *Venture Banking*
A venture banking firm is comparing two ventures that are competing for an available $1 million in start-up cash. After this initial investment, the following operating costs and revenues (in $ × 10^3) are expected during the next eight years.

	A Operating		B Operating	
Year	**Cost**	**Revenue**	**Cost**	**Revenue**
1	100	370	300	0
2	100	370	300	0
3	100	370	300	0
4	100	370	300	1170
5	100	370	300	1170
6	100	370	300	1170
7	100	370	300	1170
8	100	370	300	1170

(*a*) Using a discount rate of 15%, calculate net present value, benefit-cost ratio, and net benefit-cost ratio for both A and B. Which venture should be undertaken?
(*b*) Same as (*a*), but with 20% discount rate.

13.5. *Machine Purchase*
The manager of a production plant has space for one new machine. The possible choices, with estimates of costs and benefits, are shown below. Each machine is assumed to have a five-year life.

	Values of machine ($ × 10^3)			
Benefits and cost items	**A**	**B**	**C**	**D**
Initial cost	72	25	189	26.8
Annual net benefits	20	7.45	50	8
Salvage value at end of life	0	0	15	0

(*a*) For each machine, using a discount rate of 8%, calculate the net present value, the benefit-cost ratio, and the payback period.
(*b*) Which machine should be chosen? Why?

13.6. *Mine Road*
A mining company wishes to build a road to a new quarry which, according to best estimates, will be productive for ten years. The benefits of the road will be $2M a year for ten years, after which it will be abandoned. The company has to decide among a macadam, an asphalt, or a concrete road.

	Cost of pavement type ($M)		
Type of cost	**Concrete**	**Asphalt**	**Macadam**
Initial, K	7	5.8	3
Annual maintenance, A	0.2	0.45	1

Using 8 and 15% discount rates, rank the alternatives by the two types of benefit-cost ratios, $(B - A)/K$ and $B/(K + A)$, and by net present value. Which road should the company choose?

$$P = \frac{R}{crf} \qquad \frac{1}{crf} \text{ for } 8\% = 8.56 \qquad \frac{1}{crf} \text{ for } 15\% = 5.85$$

13.7. *Null Alternative*
A company, whose discount rate is 5%, may choose to invest in one of the three projects described below:

	Project		
Characteristic	**A**	**B**	**C**
Initial cost, $M	31	26	37
Annual benefits, $M	5	5	10
Project life, years	10	8	5

(*a*) Rank the projects by benefit-cost ratio, net present value, and internal rate of return. Which project do you recommend?
(*b*) Sketch the stream of benefits the company may expect to receive on its $40M current capital over the next ten years for each project, including the null alternative. Now which project will you recommend?

13.8. *Strip Mine*
A strip mine, which eventually will have to be reconverted to a forest, is expected to have the following costs and benefits ($M):

Year	Cost	Benefit	
0	10		
1		5	
2		10	
3		15	
4–14			(breaks even)
15	25		(clean up)

(*a*) For each of the following discount rates, evaluate the project by net present value and determine whether it ought to be implemented: $r = 0\%$; $= 100\%$; $= 10\%$
(*b*) Calculate the internal rate of return. Does this mean the project is worthwhile?

13.9. *Alternatives*
Compare the following investments on the basis of the net present value, benefit-cost, net benefit-cost, and internal rate of return:

		Benefits and costs by year ($M)					
Investment	**Item**	**0**	**1**	**2**	**3**	**4**	**5**
1	Benefits	0	30	75	111	0	0
	Costs	90	10	25	37	0	0
2	Benefits	0	34	34	34	34	34
	Costs	75	9	9	9	9	9

Which alternative would you recommend to maximize profits, assuming an 8% opportunity cost of money?

13.10. *New Car (Again)*
See Problem 11.2. Having calculated the present value of benefits and costs,
(*a*) Evaluate this model by net present value, benefit-cost ratio, and the internal rate of return.
(*b*) Is the car a good buy? Discuss your answer.

13.11. *Transit System*
Suppose you are hired by the mayor to evaluate two sets of designs for improving the local transit system. Their costs and benefits are, in $ × 10^3:

Plan	Initial cost	Annual benefit
A	200	30
B	600	75

The mayor tells you to assume a 20-year life for the systems and to use a discount rate of 8%.
(*a*) Calculate the net present value and benefit-cost ratio for each of these designs.
(*b*) Do you think 8% could correctly reflect the discount rate? Why or why not?
(*c*) Assuming 8% is the correct opportunity cost, which design should the mayor choose? Discuss the basis for this selection.

13.12. *Criteria Review*
What are the advantages and disadvantages of each of the following criteria:
(*a*) benefit-cost ratio
(*b*) net benefit-cost ratio
(*c*) internal rate of return
(*d*) net present value

13.13. *Easy Start*
Ready-Tech's sales manager (see Problem 11.10) approaches a lab that uses the two-year payback method of evaluating commitments to new equipment. The lab would have to spend $8000 on space changes to accommodate the machine. They would then save $12,000/yr in labor costs, which, under the $10,000/yr "Regular" lease would give them a net savings of $2000/yr. The lab discount rate may be assumed to be 20%.
(*a*) What is the lab's payback period under the "Regular" lease? Under the "Easy Start" lease with initial payments of $7000?
(*b*) Should the lab acquire the machine under "Easy Start?" Discuss your evaluation.

CHAPTER 14

COST ESTIMATION

14.1 THE PROBLEM

Costs are a crucial element in systems analysis. As stressed in Chapter 1, optimal design requires a full consideration of values on a par with the technical aspects. It is meaningless to talk of a best design if one has not factored in costs: as defined by the production function (Chapter 2), there are a multitude of technically efficient combinations that may produce a desired result. Costs or relative values are the means to identify the truly best designs from the many technical candidates. The optimality conditions of Section 4.2 make this point clear: the optimum is defined by an equal weighting of Marginal Products and Marginal Costs.

Despite the importance of costs, engineers and designers tend to minimize their role in systems analysis. This is a natural psychological problem: we all normally focus on the areas we know and disregard the others. Thus it is usual for engineers to imagine simplistically that costs are something you can "look up" or "get from the accountants." This is a fundamental mistake that can have profound consequences.

The fact is that it is difficult to determine the costs to use in a systems analysis. The most obvious figures are likely to be wrong; if they are used the design is almost certainly going to be poor. The problem is to determine the appropriate costs. To do so, a systems analyst must deal with several issues, each discussed in turn in this chapter. These concern:

- *Estimation*, the measurement of the concept
- *Concepts*, the correct idea about what is to be estimated
- *Dynamics*, the variation in costs over time
- *Technological Choice*, the further variation in costs due to fundamental changes in the structure of costs