ECONOMICS OF TELECOMMUNICATIONS SYSTEMS

Telecommunications engineering problems are generally formulated in the context of business, government, or social problems. In the long run, feasible engineering solutions to these problems must provide benefits greater than their implementation and operational costs, that is, solutions must have positive value. Although there are various ways to measure value, decision makers in free-market economics tend to focus on financial metrics, which are based on economic factors.

In this article, we describe the overall telecommunications planning problem using a business-driven approach that emphasizes business requirements and revenue opportunities in addition to cost-reduction technology choices. The focus of the article is the business justification task of the strategic telecommunications planning process and specifically the economic valuation of telecommunications investment decisions.

At a strategic business level, in order to understand benefits and costs, the analysis of economic value in the dynamic telecommunications industry environment must take into consideration the strategic value and implications of the fundamental external forces that drive telecommunications change, namely technology, user demands, and industry structure. These issues are discussed in the section titled "Strategic Telecommunications Planning" in which decision-making models are presented in the context of fundamental forces of change in the telecommunications industry, namely technology, user demands, and industry structure.

The section entitled "Evaluation of Telecommunications Investment Decisions" presents the fundamental financial accounting and computations required to evaluate telecommunications projects. It develops two basic investment decision models: the net present value model and the economic value added model. The following section provides details on cost and revenue factors. The methodology presented in this section considers capital, life-cycle, operational, and technology costs. It captures benefit effects by modeling service market, price, and take-rate projections. Technology trends and market environment effects such as competition and privatization are modeled to complete the information set that is used to understand the engineering economic issues.

Typical analyses cover future time windows and as such deal with uncertain information. The section entitled "Evaluation of Telecommunications Investment Decisions under Uncertainty" introduces techniques that are used to understand these uncertainties in the context of the decision-making process. The uncertainties are analyzed using simulation techniques that produce an understanding of the financial risks of the proposed solutions. Techniques for managing project risks are presented.

The next section introduces business modeling techniques from modern finance to deal with the dynamic nature of information during the execution of a project. These techniques explicitly recognize that the initial evaluation of a project and hence the decision to initiate a project use incomplete information. The methodology is adapted from the modeling of financial derivative securities. Derivative security option analysis techniques are generally used to understand the value accrued from delayed decisions and evolving information. This approach more accurately reflects the processes actually executed during a telecommunications engineering project. Decisions are made dynamically throughout the duration of the project and use the best information available at the time of the decision. The final section provides a brief summary of the discussions.

All economic results in this article are presented using standard financial accounting measures from which any set of desired financial decision metrics can be computed. This facilitates the discussions among project managers and executives in which financial understanding is a necessary condition for decision-making.

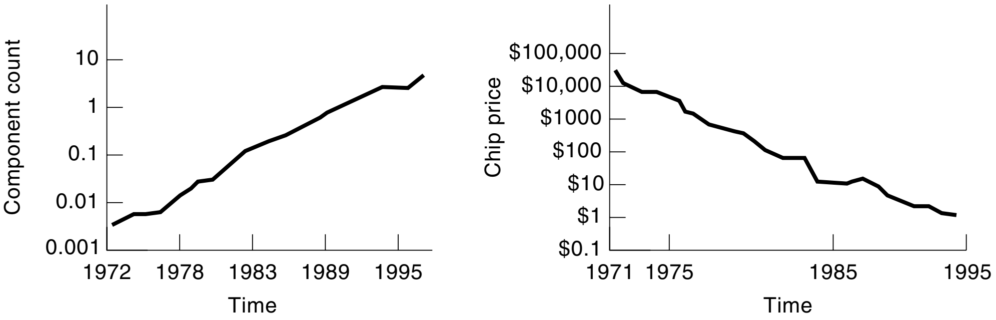


Figure 1. Component count per chip doubles every 18 months while chip prices decrease 37% annually.

STRATEGIC TELECOMMUNICATIONS PLANNING

Investment decision-making in the dynamic revolutionalized telecommunications industry environment must take into consideration the strategic value and implications of the three fundamental external forces that drive telecommunications change, namely, technology, user demands, and industry structure. The selection of basic technology options is expanding, and for each option there is a growing array of products from an increasing number of suppliers. Technology advances are continuously producing price and performance improvements in microelectronics, progress in computing and software, and a dramatic emergence of photonics or light-wave communications. As illustrated in Fig. 1, in microelectronics, the component count per chip has been doubling every 18 months for 20 years and it is expected to reach a pace of doubling every 12 months. Over these years, we have seen a 59% annual increase in chip capacity and a 37% annual decrease in price.

In computing, microcomputer-based systems have doubled in processing power every year, while at the same time, costs have declined annually between 18% and 34% depending on system scale. Photonics or light-wave technology, the third enabling technology engine, embraces optical fiber and the devices that make it usable. About ten years ago, light-wave systems made their first commercial appearance in long-distance telephone networks. At that time, typical light-wave communications systems operated at 90 to 135 megabits per second with signal repeaters spaced a few miles apart. Today, the majority of all traffic in telecommunications networks is carried on light-wave systems; most of it is on gigabit per second lines with repeaters spaced more than 20 miles apart.

The dramatic decrease in technology cost and the associated increase in bandwidth or capacity present opportunities for the creation and delivery of high value-added services and applications, along with opportunities for substantial increase in business volume. The growth in the on-line and Internet-based services is but one example of this effect. The result is a major shift of the telecommunications industry focus, from provisioning of the basic resource (i.e., bandwidth) to competing in delivering high value-added services to users.

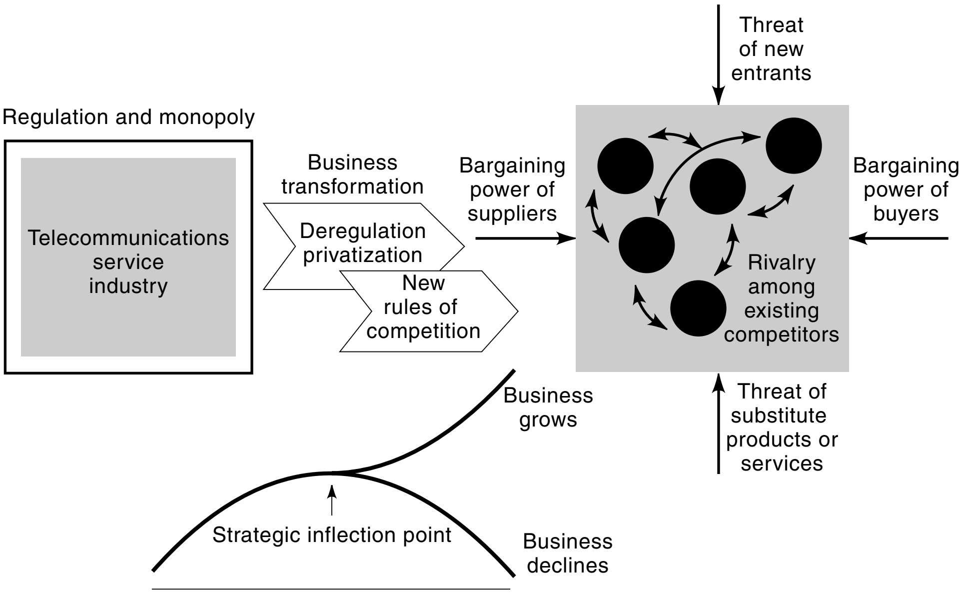
The effect of industry structure on telecommunications investment decisions can be analyzed using the framework first proposed by Porter's seminal work (1) on competitive strategy analysis. Based on Porter's framework of competitive advantage, the structure of the industry is embodied in five forces that collectively determine industry profitability: the power of buyers, the power of suppliers, the threat of new entrants (or potential competitors), the threat of substitute products, and the rivalry among existing competitors. Recent modifications of competitive theory suggest the consideration of one additional force, the force of complementors, which are other businesses from which customers buy complementary products (2).

Porter's model captures the characteristics of a competitive market, unregulated by any external agency or government. By extending it to take into consideration the effect of government actions, it can be used to study the structure of the telecommunications industry environment, which is in the process of business transformation, driven by technology and market drivers (such as business globalization and technology development and convergence), and most importantly deregulation and privatization (the end of government monopolies and subsidies). The impact of these fundamental changes that transition a previously regulated environment into a competitive environment is enormous. These changes represent a crisis point, referred to as a strategic inflection point (2). This is the point at which the old strategic picture dissolves and gives way to a new radically different competitive environment. It presents both a threat and an opportunity. The businesses that adapt their strategies to the new competitive environment will ascend to new heights. The businesses that do not will decline. These concepts are illustrated in Fig. 2.

To identify, analyze, and justify investment decisions in the emerging dynamic telecommunications environment a business-driven methodology, such as the one shown in Fig. 3 (3), is needed. The main tasks of the methodology are as follows.

- *Strategic business modeling.* This task analyzes business requirements and revenue opportunities and identifies the business applications or services that need to be supported by the network infrastructure.
- *Industry and technology trends analysis.* This task identifies and analyzes the implications of technology advances and time lines in terms of time of introduction, maturity, acceptability, and standards on business processes, functions, and applications.
- *Network strengths, weaknesses, opportunities, and threats analysis.* This task assesses the corporation's usage of network technology and develops an inventory of the current network infrastructure. The task identifies the strengths and weaknesses of the current network infra-

Figure 2. The telecommunication industry environment is in the process of business transformation, driven by technology and market factors (such as business globalization and technology development and convergence), and most important deregulation and privatization. The impact of these fundamental changes that have resulted in a transition from a previously regulated environment into a competitive environment is enormous. These changes represent a crisis point, referred to as a strategic inflection point. This point is where the old strategic picture dissolves and gives way to a new, radically different competitive environment.



structure, the opportunities to apply technology to enhance network strategy, and the barriers to utilize network solutions successfully to support business directions.

- *Network architecture planning.* This task develops network architectures that take advantage of technology capabilities to support business application requirements efficiently. This phase of network architecture planning is decoupled from the physical network implementation. The emphasis is on developing functional architecture models that specify the key functions and their interactions.
- *Network planning and design.* This task determines short-, medium-, and long-term network plans for technology deployment according to the defined network architecture, and uses optimization techniques to determine the values of the network design variables that minimize the total network infrastructure cost, while meeting all constraints.
- *Business justification and transition planning.* This task

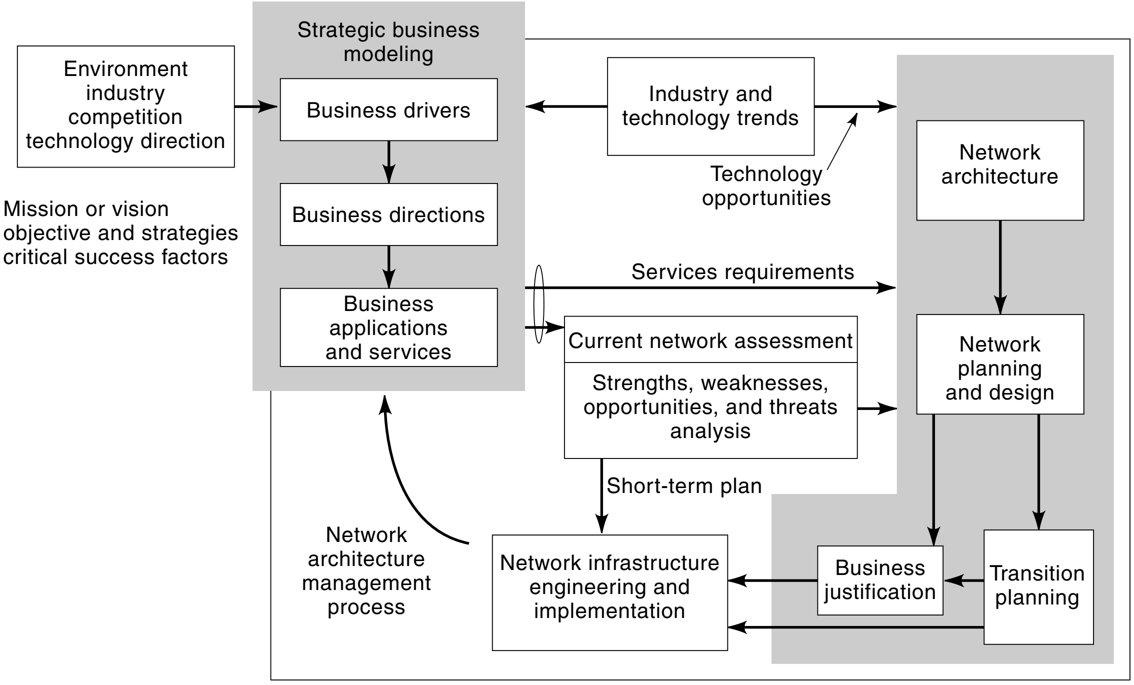


Figure 3. Strategic network planning process used to identify, analyze, and justify investment decisions in the emerging dynamic telecommunications environment.

identifies the strategies that will be followed and the actions that will be taken to close the gap between the current and the desired state of the corporate network infrastructure. The task uses a variety of engineering economic methods and tools to evaluate alternatives and provide business justification for network technology investment recommendations.

- *Network infrastructure engineering and implementation.* This task addresses detailed engineering and network infrastructure deployment and implementation issues.

EVALUATION OF TELECOMMUNICATIONS INVESTMENT DECISIONS

In this section we discuss how telecommunications investments create economic value and review the core value drivers. For illustration purposes we structure the discussion around the concept of the value created by a telecommunications service. Let B denote the perceived benefit of a telecommunications service per unit consumed, that is, the value that consumers derive from the service. The perceived benefit B is defined as perceived gross benefit minus user, transaction, and purchasing costs, where the perceived gross benefit of the service depends on service attributes, such as performance, reliability, and functionality; user, transaction, and purchasing costs include all costs associated with using the service (the purchase price is not included). Furthermore, let C denote the cost for providing the service, expressed per unit of service (note that C represents the average cost and not the total cost for providing the service) and P the service's monetary price. Then

$$\begin{aligned}\text{Value created} &= \text{Perceived benefit to consumer}\\ &\quad - \text{Cost of inputs} = B - C\\ \text{Service provider's profit} &= \text{Monetary price of service}\\ &\quad - \text{Cost of inputs} = P - C\\ \text{Consumer surplus} &= \text{Perceived benefit to consumer}\\ &\quad - \text{Monetary price of service} = B - P\end{aligned}$$

Note that the value created is equal to the service provider's profit plus consumer surplus; therefore the price P determines how much of the value created is captured by the service provider as profit and how much is captured by consumers as consumer surplus. The tradeoff that a consumer is willing to make between price P and any benefit-enhancing or cost-reducing service attribute depends on the characteristics of the consumer indifference curve, which for a given consumer, yields for any (price, attribute value) combination along the curve the same consumer surplus. An example is shown in Fig. 4, where two consumer indifference curves, EF and EG with different slopes, are shown. The consumer surplus is constant for each (price, attribute value) combination along each curve. In the case of the curve EG, the consumer is willing to pay a higher price $P_G - P_E$ for an improvement $\Delta_A = A_F - A_E$ in the value of the service attribute than the consumer that follows the curve EF, even though the consumer surplus is the same in both cases. Furthermore, note that the increase in price along a given indifference curve corresponds to the incremental benefit Δ_B caused by an improvement Δ_A in the value of the service attribute. This is obvious, since as shown in the figure $(\text{consumer surplus})_E = B_E - P_E = (\text{consumer surplus})_F = B_F - P_F$, which implies that $\Delta_B = B_F - B_E = P_F - P_E$.

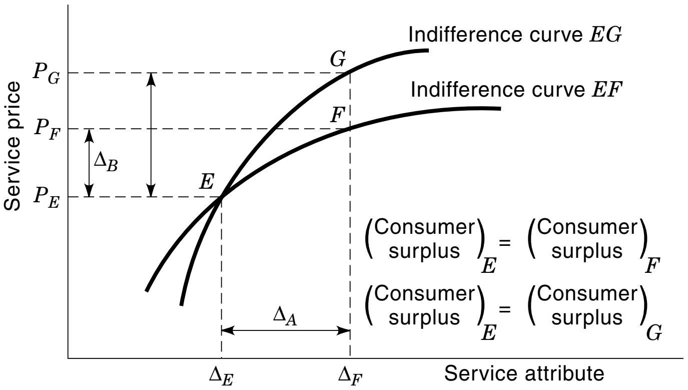


Figure 4. Two consumer indifference curves, EF and EG, with different slopes. The consumer surplus is constant for each (price, attribute value) combination along each curve. In the case of curve EG, the consumer is willing to pay a higher price, $P_G - P_E$, for an improvement, $\Delta_A = A_F – A_E$, in the value of the service attribute than the consumer that follows curve EF, even though the consumer surplus is the same in both cases.

Based on the definition of value creation given above, a telecommunications investment decision can create value by

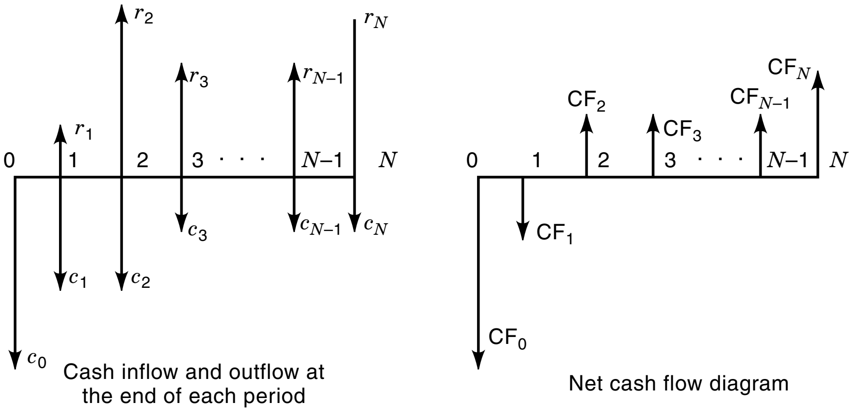
- Introducing a service that improves the perceived consumer benefit for the same cost (i.e., maintain cost parity) or perhaps higher cost (i.e., achieve cost proximity), and therefore create a differentiation advantage
- Reducing the cost of delivering the service for the same perceived benefit (i.e., maintain benefit parity), or perhaps lower perceived benefit (i.e., achieve benefit proximity), and therefore create a cost advantage

In general, markets characterized by relatively steep consumer indifference curves favor differentiation strategies, while markets characterized by relatively flat consumer indifference curves favor cost advantage strategies. The choice of the best strategy depends on a number of factors such as the price elasticity of demand and market structure (4). Finally, note that to achieve competitive advantage (i.e., outperform the industry norm) a telecommunications firm must not only create positive value, it must create more value than its competitors.

The valuation of business decisions such as telecommunications investment decisions requires the consideration of economic costs, which are based on the concept of opportunity cost. Based on this concept, the economic cost of deploying resources in support of a particular activity is equal to the economic value of the best foregone alternative use of resources. In the following, we discuss two telecommunications investment decision models that are based on this concept.

- Net present value (NPV) or cumulative discounted cash flow (CDCF) method
- Economic profit or economic value added (EVA) method

Other decision models such as the internal rate of return and the payback period can be used to valuate telecommunica-



Cash inflow and outflow at the end of each period

Net cash flow diagram

Figure 5. Net cash flow, CF$_n$, at the end of period n is computed by subtracting from all related project cash inflows (revenues), r_n, all project-related cash outflows, c_n (expenses other than depreciation plus income taxes and capital expenditures), i.e., CF$_n$ = r_n–c_n.

tions investment decisions, but the NPV and EVA methods are considered to be the best investment valuation methods.

Net Present Value Method

Consider a telecommunications investment that generates a net cash flow (CF$_n$) at the end of period n, where n denotes time measured in discrete compounding periods. Let N denote the project planning horizon. The net cash flow CF$_n$ at the end of period n is computed by subtracting from all related project cash inflows (revenues) r_n all project related cash outflows c_n (expenses other than depreciation plus income taxes and capital expenditures), that is, CF$_n$ = $r_n - c_n$. Figure 5 illustrates the concept of net cash flow.

To compute the cash flow we first compute the pretax operating income earned, which includes most revenues and expenses. This is referred to as the earnings before interest and taxes (EBIT). Depreciation of fixed assets should be subtracted in calculating EBIT. The EBIT is used to calculate the net operating profit less adjusted taxes (NOPLAT), which represents the after-tax operating profits after adjusting the taxes to a cash basis through the following expression: NOPLAT = EBIT × (1 − tax rate). The cash flow from operations at the end of a period n is equal to NOPLAT plus depreciation. Summarizing the above we have for each period n:

$$\begin{aligned}
\text{Cash flow from operations}&\\
&= \text{Cash inflows} - \text{Cash outflows}\\
&= \text{Revenues} - \text{Expenses other than depreciation}\\
&\quad - \text{Income taxes}\\
&= \text{NOPLAT} + \text{Depreciation}\\
&= \text{EBIT} \times (1 - \text{Tax rate}) + \text{Depreciation}
\end{aligned}$$

where

$$\begin{aligned}
\text{EBIT} &= \text{Revenues} - \text{Expenses other than depreciation}\\
&\quad - \text{Depreciation}\\
\text{Income taxes} &= \text{EBIT} \times \text{Tax rate}
\end{aligned}$$

From the preceding expressions we note that depreciation affects the cash flow only through its impact on income taxes. Depreciation is not a cash expense; it is a way to spread the cost of an asset over the asset's life, from an accounting point of view.

The net cash flow is equal to cash flow from operations minus capital expenditures. The net present value of the net cash flow CF$_n$ is equal to the amount of money that must be invested today at the rate of return k so that after n time periods (for example, years) the principal plus interest equals CF$_n$. Mathematically, the net present value NPV(k, n) is given by the following expression:

$$\mathrm{NPV}(k,n) = \frac{\mathrm{CF}_n}{(1+k)^n}$$

The discount rate (or cost of capital) k reflects the opportunity cost to all capital providers weighted by their relative contribution to the total telecommunications investment. This is generally referred to as the *weighted average cost of capital* (WACC), and can be calculated from the following expression:

$$k = \sum_{i=1}^{m} p_i k_i$$

where there are m types of financing sources in proportions p_i, $i = 1, \ldots, m$ of total capital, each source with its own cost of capital k_i. Examples of financing sources include equity, such as sales of stocks and retained earnings, or debt, such as the sale of bonds or short-term borrowing.

The net present value NPV(k) of a stream of cash flows received over the entire project lifetime N is the sum of the present values of the individual sums,

$$\mathrm{NPV}(k) = \sum_{n=0}^{N} \frac{\mathrm{CF}_n}{(1+k)^n}$$

To illustrate the use of the NPV valuation approach, we consider as an example a telecommunications company that is valuating an investment decision related to the modernization of its network infrastructure. The total investment under consideration is equal to \$120 million, to be invested during the first two years of the project, \$60 million each year. The asset depreciation schedule is based on the straight-line method, with a depreciation lifetime of five years, starting one year after the assets are placed in service. The project planning period is assumed to be ten years. The effective tax rate is 35%.

The procedure for computing the project net cash flow is shown in Table 1. The table shows the estimated revenues and operating expenses (other than depreciation) for the ten-year project planning horizon. The project earnings before in-

Table 1. Example of Telecommunications Investment Decision Valuation (amounts in millions)

Project Year	1	2	3	4	5	6	7	8	9	10
Revenues	9.7	60.0	62.6	68.6	76.5	82.2	84.0	84.1	83.9	83.6
Operating expenses	2.3	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5
Taxes										
EBITDA	7.4	55.3	57.8	63.7	71.5	77.1	78.8	78.8	78.5	78.1
Depreciation	0.0	10.0	20.0	20.0	20.0	20.0	10.0	0.0	0.0	0.0
EBIT	7.4	45.3	37.8	43.7	51.5	57.1	68.8	78.8	78.5	78.1
Taxes	2.6	15.9	13.2	15.3	18.0	20.0	24.1	27.6	27.5	27.3
NOPLAT	4.8	29.4	24.6	28.4	33.5	37.1	44.7	51.2	51.0	50.8
Cash flow	4.8	39.4	44.6	48.4	53.5	57.1	54.7	51.2	51.0	50.8
Capital expenditures	60.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net cash flow	−55.2	−30.6	24.6	28.4	33.5	37.1	44.7	51.2	51.0	50.8
Net present values										
DCF	−49.7	−24.8	18.0	18.7	19.9	19.8	21.5	22.2	19.9	17.9
CDCF	−49.7	−74.5	−56.6	−37.8	−18.0	1.9	23.4	45.6	65.6	83.5

terest, taxes, depreciation, and amortization (EBITDA) are equal to project revenues minus operating expenses. The project EBIT is equal to EBITDA minus depreciation. Based on the project EBIT, the assumed effective tax rate of 35%, and the assumed capital expenditures, we compute the project NOPLAT, the cash flow from operations, and the net cash flow for each year. To compute the present value of the net cash flow, and the cumulative discounted net cash flow (CDCF) we assume a 11% weighted average cost of capital (WACC). The CDCF and the net cash flow is shown in Fig. 6 for each year of the project planning period under consideration.

The results shown in Table 1 and Fig. 6 indicate that the telecommunications investment under consideration has a negative CDCF for the first five years of the project, becomes positive the sixth year, and reaches a value of $83.5 million, which is the project NPV, when considering the entire ten-year project planning horizon.

To study the effect of the value of the cost of capital on the NPV, in Fig. 7 we plot the project NPV as a function of the cost of capital. As shown in the figure, the project NPV decreases monotonically with the cost of capital. Assuming a ten-year project planning horizon the project has a positive NPV for cost of capital less than 30% and a negative NPV for cost of capital 30% and above. The cost of capital threshold becomes 25% if we consider an eight-year planning horizon, and 12% if we consider a six-year planning horizon.

Economic Profit Method

The economic profit or economic value added (EVA) method measures the economic value created by a telecommunications investment in a single period of time (e.g., a year), and is defined as follows:

$$\begin{aligned}\text{Economic value added} &= \text{Invested capital} \times (\text{ROIC} - \text{WACC})\\ &= \text{NOPLAT} - (\text{Invested capital} \times \text{WACC})\end{aligned}$$

where, the return on investment (ROIC) is defined as

$$\text{ROIC} = \text{NOPLAT}/(\text{Invested capital})$$

Based on its definition, EVA is a method of measuring the profitability of a telecommunications investment that takes into account the opportunity cost the company incurs by having its capital tied up in the specific project. Comparing the concept of EVA with the concept of NPV, we note that the EVA can be thought of as an annualized NPV calculation.

To illustrate the use of the EVA method, we discuss the impact of an investment on the income statement and balance

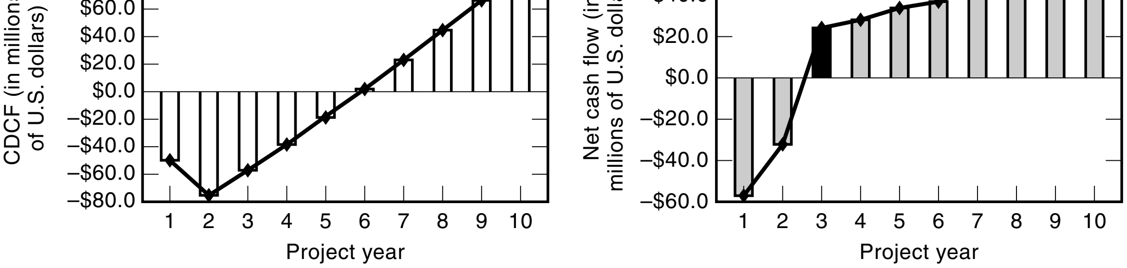


Figure 6. CDCF and net cash flow for each year of the 10-year project planning period. The total investment under consideration is equal to $120M, to be invested during the first two years of the project, $60M each year. The asset depreciation schedule is based on the straight-line method, with a depreciation lifetime of 5 years, starting one year after the assets are placed in service. The effective tax rate is 35%, and the WACC 11%.

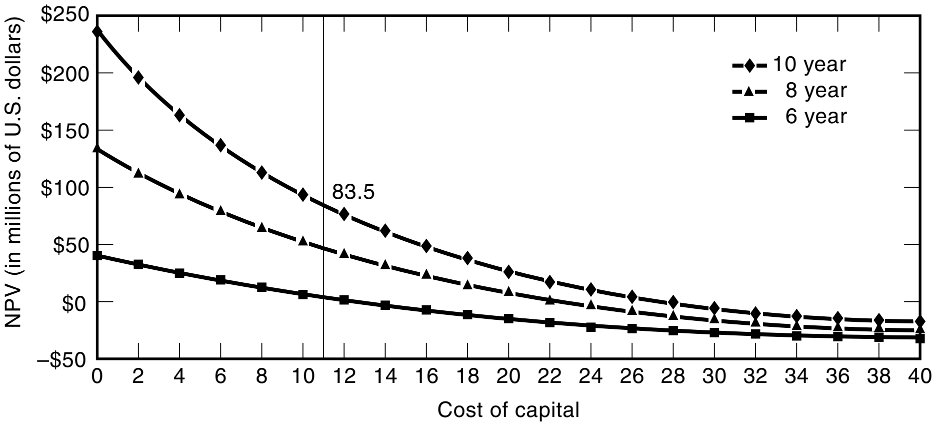


Figure 7. Effect of the value of the cost of capital on NPV. The project NPV decreases monotonically with the cost of capital. Assuming a 10-year project planning horizon, the project has a positive NPV for cost of capital less than 30%, and a negative NPV for cost of capital 30% and above. The cost of capital threshold becomes 25% if we consider an 8-year planning horizon, and 12% if we consider a 6-year planning horizon.

sheet of a telecommunications company, using the example shown in Table 2. In this example we evaluate two network infrastructure investments, referred to as *option A* and *option B*. The two options present the same revenue-generating capability, but they differ on their effect on the company's operations expenses, due to different network designs and associated use of technology. For the purposes of this example we assume an effective tax rate of 40%, a ten-year straight-line depreciation and amortization schedule, and a 11% WACC. Based on the data shown in Table 2, option B results in a 40% reduction in network operations, 25% reduction in depreciation and amortization, and a 25% reduction in net property, plant, and equipment. The operating income (EBIT) and the NOPLAT are EBIT_A = $1,188 million, NOPLAT_A = $713 million, and EBIT_B = $1,759 million, NOPLAT_B = $1,055 million, for options A and B, respectively. To compute the EVA, first we compute the invested capital and the ROIC. The invested capital is the sum of the working capital (which is equal to current assets minus current liabilities) plus the net property, plant, and equipment plus other assets, minus other liabilities. The ROIC for option A is 12%, which for a WACC equal to 11% implies a 1% spread. On the other hand, for option B, the ROIC is 23.8% and the spread is 12.8%. The EVA for op-

Table 2. Example of an EVA Calculation

Summary of Income Statement ($ millions)	Option A	Option B
Revenue	4,215	4,215
Expenses		
Access charges	50	50
Network operations	1,054	632
Customer operations	767	767
Corporate operations	556	556
Operating expenses (other than depreciation)	3,627	2,906
Depreciation and amortization	600	450
Total operating expenses	3,027	2,456
Operating income (EBIT)	1,188	1,759
Effective tax rate	40%	40%
Net operating profit less adjusted taxes (NOPLAT)	713	1,055
Summary of balance sheet ($ millions)	**Option A**	**Option B**
Assets		
Current assets	1,226	1,226
Net property, plant, and equipment	6,000	4,500
Other assets	669	669
Total assets	7,895	6,395
Liabilities and equity		
Current liabilities	1,416	1,416
Other liabilities	537	537
Deferred taxes	1,437	1,437
Debt	1,708	1,139
Equity	2,797	1,866
Total equity and liabilities	7,895	6,395
Invested capital	5,943	4,443
ROIC	12.0%	23.8%
EVA	59	567

tions A and B is equal to $EVA_A = 59$ and $EVA_B = 567$, which implies that option B adds a substantially higher economic value to the company than option A.

COST AND REVENUE FACTORS

As discussed in the section entitled “Strategic Telecommunications Planning” and illustrated in Fig. 8, the economic valuation of telecommunications investment decisions requires the identification of all relevant project cost and revenue factors. These factors depend on the market opportunity expressed in terms of the associated user demands and the characteristics of the telecommunications network infrastructure that is required to take advantage of the market opportunity. The network structure itself is heavily influenced by business and user needs and technology opportunities.

Cost Factors

The costs associated with a telecommunications project include capital investments in communications equipment (both hardware and software) and a number of operational expenses (which include support, operations, maintenance, marketing, and sales costs among others). When evaluating a telecommunications investment decision, only the avoidable costs related to the decision should be considered. These are the costs that can be avoided if certain choices are made, and should not be confused with the sunk costs, which are the costs that have been incurred and cannot be recovered. The sunk costs are independent of the specific decision under consideration and therefore should be ignored. Sunk costs are important in analyzing the attractiveness and structure of the telecommunications industry, mainly due to their importance in market entry and exit decisions.

The costs associated with a telecommunications project for a given planning horizon can be classified as either fixed costs (FC) or variable costs (VC) (indirect costs or direct costs). Fixed costs, such as general and administrative expenses, remain constant as the project output increases. Variable costs, such as operations and maintenance, increase as project output increases.

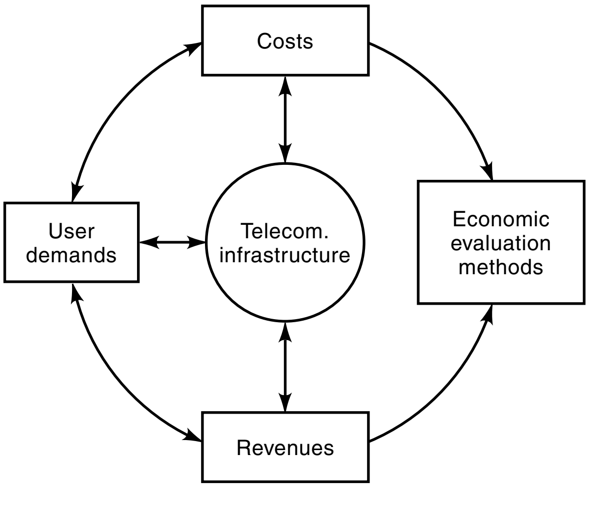


Figure 8. The economic valuation of telecommunication investment decisions requires the identification of all relevant project cost and revenue factors. These factors depend on the market opportunity expressed in terms of the associated user demands and the characteristics of the telecommunication network infrastructure that is required to take advantage of the market opportunity. The network structure itself is heavily influenced by business and user needs and technology opportunities.

The relationship between the total project costs (TC) and the project output (or volume) V is described by the total cost function $TC(V)$, which can be expressed as $TC(V) = FC + VC(V)$. Since fixed costs FC are independent of project output, while variable costs VC increase as project output increases, total project costs TC increase monotonicaly with the project output. The total cost function is said to exhibit economies of scope if $TC(V_x) + TC(V_y) \geq TC(V_x, V_y)$, that is, it is less expensive to offer two services x, y using one network infrastructure with a total cost function $TC(V_x, V_y)$ than it is to offer them over separate networks with total cost function $TC(V_x) + TC(V_y)$.

Two important functions related to the total cost function are the average cost function $AC(V)$ and the marginal cost function $MC(V)$. The average cost function, defined as $AC(V) = TC(V)/V$, describes how the average costs vary with the amount of project output. As shown in Fig. 9, depending on whether the average costs decrease, increase, or remain constant with respect to project output, we have economies of scale, diseconomies of scale, or constant returns to scale, respectively. The smallest level of project output at which economies of scale are exhausted is known as the minimum efficient scale. The shape of the average cost curve in Fig. 9 can be explained if we note that the average cost is equal to the sum of the average fixed cost $AFC(V) = FC/V$ plus the *average* variable cost $AVC(V) = VC(V)/V$. Fixed costs are independent of output; therefore their average value (or per-unit amount) declines as output increases. On the other hand, average variable costs increase as project output increases. The combination of these two effects yields an average cost that initially decreases as project output increases, and then after reaching a minimum value, increases as project output increases.

The marginal cost function $MC(V)$ describes the rate of change of total costs with respect to output, that is, $MC(V) = dTC(V)/dV$. Marginal cost represents the incremental cost required to produce an additional unit of output. A general relationship between marginal and average cost can be derived from the definition of the marginal cost: if the average cost is a decreasing function of output, then $MC(V) < AC(V)$; if average cost is independent of output, then $MC(V) = AC(V)$; if the average cost is an increasing function of output, then $MC(V) > AC(V)$.

As shown in Fig. 8, the total project costs both depend on and influence the characteristics of the network structure. Properly defined cost models express network component cost as a function of technology component attributes, that is, *component cost* $= f(attribute_i,\ i = 1, \ldots, n)$, where the function f defines the structure of the cost model. For example, in the case of a narrow-band circuit switched network component, a linear cost model of the form $A + \Sigma B_i U_i$ can be used, where the quantities A and B_i denote the fixed and variable parameters of the cost function, and U_i the value of the ith component attribute (such as the number of ports for each port type, and transmission termination facilities).

The parameters of the cost model can be estimated by combining a standard demand logistic curve that models the

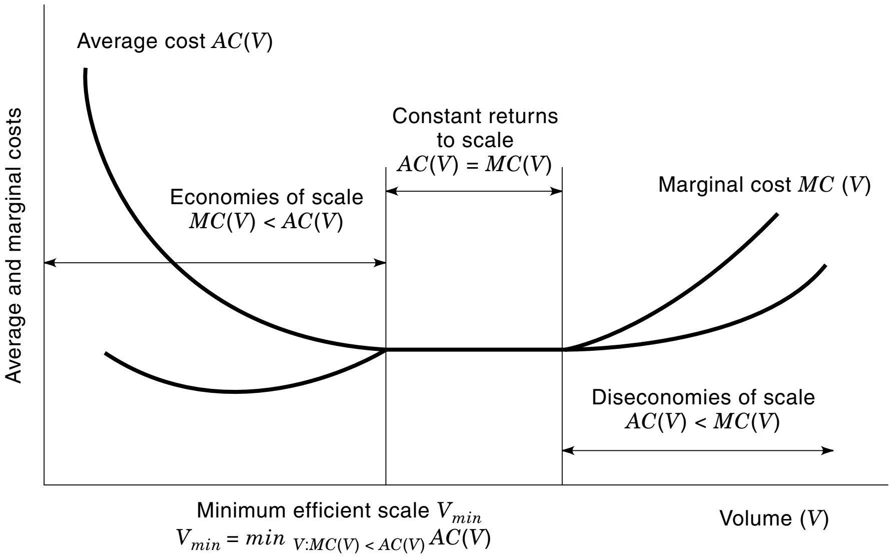


Figure 9. Two important functions related to the total cost function are the average cost function AC(V) and the marginal cost function MC(V). Depending on whether we average costs decrease, increase, or remain constant with respect to project output, we have economies of scale, diseconomies of scale, or constant returns to scale, respectively. The smallest level of project output at which economies of scale are exhausted is known as the minimum efficient scale.

growth over time of the accumulated component volume, with a learning or experience curve that models component price as a function of volume, to derive an expression for component cost as a function of time. The mathematical model for the demand logistic curve or S curve is given by the following expression:

$$Y = \frac{N}{1 + be^{-at}}$$

where a is the adoption rate parameter, which affects the vertical rate of increase in the curve; b indicates the time to adoption, which affects the lateral shift of the curve; the parameter N indicates the size of the market; and t denotes time. Examples of demand logistic curves for various values of parameters a and b are shown in Fig. 10. The mathematical model for the learning curve is $X = GK^{-y}$, where y denotes the accumulated component volume, and G and K are curve-fitting parameters. Learning-curve examples are shown in Fig. 10.

Revenue Factors

The total project revenues TR(V) are computed by the product of the project output V, expressed in units of output sold, and the price P that can be charged for each unit of output, that is, TR(V) = PV. The project output V is directly related to the user demand for the service, which is also influenced by the price of the service. The relationship between service demand, that is, the quantity that can be sold, and all the variables that influence service demand, such as service price, prices of related services, service quality, advertising, and so on, is described by the demand function. In the following we focus our discussion on the relationship between service demand (quantity) and two parameters, namely, service price and time.

For telecommunications services in most cases, the relationship between service demand and price is described by the law of demand, based on which the two variables are inversely related: the lower the price, the greater the demand; the higher the price, the smaller the demand. Another interpretation of the demand function is that it provides the highest price that the market will support for a given quantity of output. The sensitivity of the service demand to price is very important in determining a pricing strategy, because of the effect that it has on the total revenues. A metric that is used to measure this sensitivity is the price elasticity of demand E_d, which is defined as the ratio of percentage change in quantity to the corresponding percentage change in price:

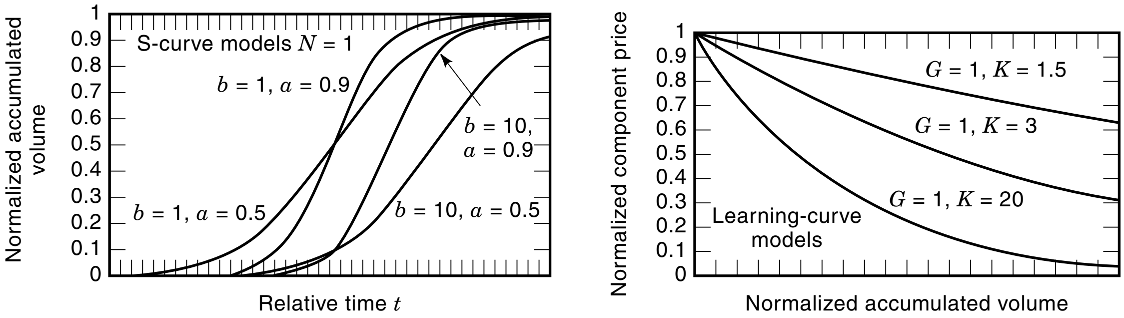


Figure 10. Examples of demand logistic and learning curves. The parameters of the cost model can be estimated by combining a standard demand logistic curve that models the growth over time of the accumulated component volume, with a learning or experience curve that models component price as a function of volume, to derive an expression for component cost as a function of time.

$$E_{\mathrm{d}} = -\frac{\%\,\Delta V}{\%\,\Delta P} = -\frac{\Delta V/V}{\Delta P/P}$$

Note that based on the definition of E_{d}, the value of price elasticity of demand may vary, depending on the reference point selected for the calculation. To avoid this ambiguity, if (P_1, V_1) and (P_2, V_2) are the two points of the curve used for the calculation of E_{d}, then we use the following values for the relevant parameters: $\Delta V = V_2 - V_1$, $\Delta P = P_2 - P_1$, $V = (V_1 + V_2)/2$, and $P = (P_1 + P_2)/2$.

If the price elasticity of demand is greater than 1, service demand is classified as elastic, which implies that a small increase in price will result in a large decrease in quantity sold. If the price elasticity of demand is less than 1, service demand is classified as inelastic, which implies that a relatively large increase in price will result in a small decrease in quantity sold. In this case, it is likely that a service price increase will increase total revenues, because the effect of the price increase is stronger than the effect of the demand decrease. The relationship between project revenues and price elasticity of demand can be described by the following expression:

$$\mathrm{MR} = P\left(1 - \frac{1}{E_{\mathrm{d}}}\right)$$

where MR denotes the marginal revenue, which is analogous to the marginal cost concept and describes the rate of change of total revenues with respect to output, that is $\mathrm{MR}(V) = d\mathrm{TR}(V)/dV$. Note that if the demand is price elastic, that is, $E_{\mathrm{d}} > 1$, then the marginal revenue is positive, which implies that the increase in demand, generated by a price reduction, will result in increase in revenues. On the other hand, if the demand is price inelastic, that is, $E_{\mathrm{d}} < 1$, then the marginal revenue is negative, which implies that the increase in demand generated by a price reduction will result in reduced revenues.

The concepts of marginal cost and marginal revenues are useful in the analysis of strategies for selecting optimum quantities and prices, and in break-even comparisons. It can be shown (1) that the output level at which marginal costs are equal to marginal revenues is the operating level that produces the maximum profit. An example is shown in Fig. 11, where project costs, project revenues, marginal costs, and marginal revenues are plotted as a function of units of output. Two break-even points are identified, at 25,000 and 223,000 units of output. The point of maximum profit is between these two break-even points, and it is at 115,000 units of output, which is the point where marginal costs are equal to marginal revenues.

Up to this point the discussion has focused on the relationship between service demand and price. In the following we discuss the relationship between service demand and time. This relationship is important because it is the basis for forecasting revenues and network infrastructure resource requirements over the project planning horizon. The network resource requirements are obtained through demand models that map service demands to network infrastructure resource requirements. These requirements influence the network structure, and therefore the overall project costs, as shown in Fig. 8.

The approach for forecasting telecommunications service demand depends on the relation of the service under consideration to existing services or products. If the telecommunications service is either enhancing or substituting an existing service, forecasting is based on substitution models, while if the telecommunications service is an additional new service, forecasting is based on diffusion models. Substitution models are based on logistic curves, with the relevant parameters (adoption rate, time to adaption, and saturation level) estimated through a regression process from historical data. A number of independent variables, such as contestable household expenditure, gross domestic products, and price elasticities, impact the value of the saturation level.

Diffusion models enable the forecasting of service demand while taking into consideration effects that are believed to have an impact on demand, but which cannot be quantified through historical data. The basic approach involves the estimation of the overall market size, based on a number of user- and service-dependent parameters, such as service price, contestable household expenditure, and associated elasticities. After estimating the overall market size and assuming a service introduction date, a diffusion model is used to determine the shape of the logistic curve by which saturation is reached. An example diffusion model, which is based on the diffusion of epidemics, models diffusion as an adjustment process, influenced by the level of understanding of the characteristics and benefits of the service (5).

EVALUATION OF TELECOMMUNICATIONS INVESTMENT DECISIONS UNDER UNCERTAINTY

The telecommunications investment evaluation metrics introduced in the preceding section depend on a number of factors, such as revenues, expenses, and interest rates, which are typically characterized by a degree of uncertainty, that is, they fluctuate. To account for the presence of uncertainty in the calculation of the evaluation metrics, we treat the uncertain parameters as random variables, characterized by properly defined distribution functions. This makes the evaluation metric a random variable, which should be described in terms of properly defined statistical measures. To illustrate, let us consider the NPV(k) metric when its constituent cash flow element, CF_n, $n = 0, \ldots, N$, is a series of independent random variables, with $f(\mathrm{CF}_n)$ as probability density functions. The NPV(k) is then a random variable with its first two statistical moments, namely, average value E(NPV) and variance Var(NPV), given by the following expressions:

$$E(\mathrm{NPV}) = \sum_{n=0}^{N} \frac{E(\mathrm{CF}_n)}{(1+k)^n},\ \mathrm{Var}(\mathrm{NPV}) = \sum_{n=0}^{N} \frac{\mathrm{Var}(\mathrm{CF}_n)}{(1+k)^{2n}}$$

where $E(\mathrm{CF}_n)$ and $\mathrm{Var}(\mathrm{CF}_n)$ denote the average value and the variance of the project net cash flow at time n. In most cases the net cash flows are not independent random variables but rather correlated in some manner. If we denote by $\mathrm{Cov}(\mathrm{CF}_n, \mathrm{CF}_s)$ the covariance of CF_n and CF_s, the variance of the NPV(k) can be computed by the following expression:

$$\mathrm{Var}(\mathrm{NPV}) = \sum_{n=0}^{N} \frac{\mathrm{Var}(\mathrm{CF}_n)}{(1+k)^{2n}} + 2\sum_{n=0}^{N-1}\sum_{s=n+1}^{N} \frac{\mathrm{Cov}(\mathrm{CF}_n, \mathrm{CF}_s)}{(1+k)^{n+s}}$$

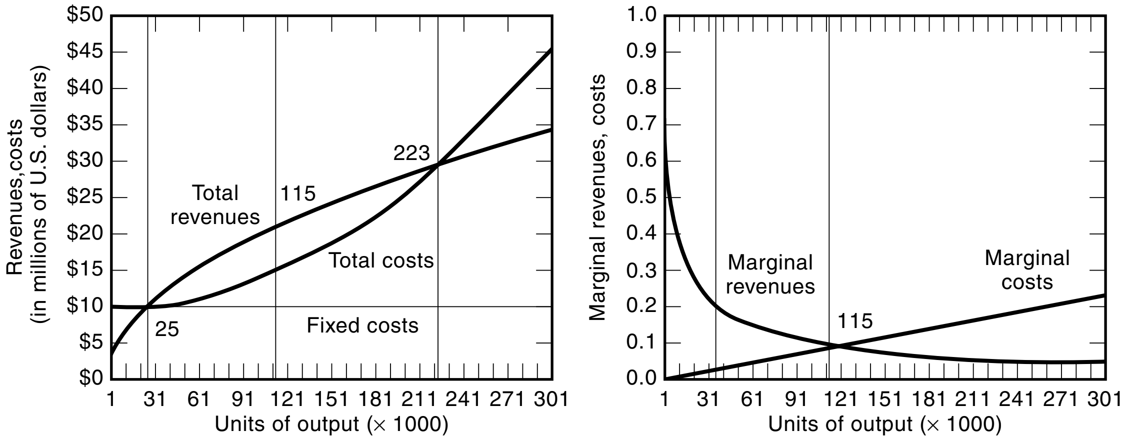


Figure 11. The concepts of marginal cost and marginal revenues are useful in the analysis of strategies for selecting optimum quantities and prices and in breakeven comparisons. The figure shows project costs, project revenues, marginal costs, and marginal revenues as a function of units of output. Two breakeven points are identified, at 25,000 and 223,000 units of output. The point of maximum profit is between these two breakeven points, and it is at 115,000 units of output, which is the point where marginal costs are equal to marginal revenues.

The preceding expressions assume that the timing of the net cash flows is known with certainty. Expressions for computing the average and variance of the NPV if this assumption is relaxed are provided in Ref. 6.

Usually the uncertainty in the cash-flow stream is due to multiple, possibly correlated random variables, such as market size, competition, service price, volume, and operating costs, which complicate substantially the analytical computation of the probability distribution of the evaluation metric. In these cases an alternative approach to risk analysis, referred to as risk simulation, should be considered. The basic steps in risk simulation are as follows: (1) specify probability distributions, time patterns, and initial investment conditions for all relevant cash flow factors; (2) for each trial run, randomly select values for all variable inputs, according to their probability of occurrence; (3) combine the simulated inputs with other known factors based on the relationships specified by the evaluation metric; (4) repeat until enough sample values have been generated to obtain the probability distribution of the evaluation metric.

To illustrate, we consider the evaluation of the telecommunications investment shown in Table 1, in the presence of uncertainty. The critical cash flow factors are the revenue stream and the operating expenses. The revenues are obtained by the total revenue function, which indicates how the sales revenues vary as a function of the volume sold. Let $P(V)$ denote the price that can be charged for the service when the sales volume is equal to V. The relationship between $P(V)$ and V is described by the demand curve, which was discussed in the section entitled "Revenue Factors." For the purposes of this example we assume that price and volume are negatively correlated, with a correlation coefficient equal to -0.65. Price and volume also depend on market conditions and the presence of competition, which is likely to reduce both price and volume sold. Let p_c denote the probability of a new market entry, and let $P_c(V_c)$ and V_c, denote the price and volume sold, respectively, in the presence of competition. P_c and V_c are also assumed to be negatively correlated with a correlation coefficient equal to -0.75.

All the preceding factors are random variables with the following distributions: (1) the market entry follows a discrete distribution, with a 40% probability of new market entry; (2) the service price follows a triangular distribution (the most likely estimates are shown in Table 3; the pessimistic and optimistic estimates are assumed to be 70% and 120% of the most likely value, respectively); (3) the volume follows a normal distribution (the average value is shown in Table 3; the standard deviation is assumed to be 10% of the average value). Finally, the operating costs are assumed to follow a truncated log-normal distribution and are assumed to be positively correlated with volume, with a correlation coefficient equal to 0.5 (the average values are shown in Table 3; the standard deviation, low bound, and upper bound, are 10%, 70%, and 120% of the average value, respectively). The probability distribution of price, volume, and expenses for the first year of the project is shown in Fig. 12.

Figures 13 and 14 show summary graphs for the service price, volume, project revenues, and project expenses for the entire project planning horizon. For each year a range of values is shown based on the distributional characteristics of the associated parameter. The range consists of two bands. The lower bound of the inner band is defined by the average value minus one standard deviation, and the upper bound by the average value plus one standard deviation. The outer band is defined by the 5th and 95th percentiles of each distribution. The summary graphs illustrate the negative correlation between price and volume and the positive correlation between volume and expenses. Referring to the project revenues summary graph, the widening of the band around the revenue average value is a measure of the increase in the uncertainty of the revenue projections with time.

The summary graph of the project net cash flow and NPV is shown in Figs. 15 and 16, respectively. The widening of the band around the average NPV value quantifies the high risk associated with the project. Assuming a ten-year project planning horizon, the 5th, 50th, and 95th percentiles of the NPV are $-\$27.4$, \$53.4, and \$84.8 million, respectively. The probability that the project will produce a negative NPV for a ten-

Table 3. Risk Analysis of Telecommunications Investment Decision Valuation

Project Year	1	2	3	4	5	6	7	8	9	10
Price (per unit in U.S. dollars)										
No market entry	65.3	79.3	107.3	102.7	88.7	86.8	84.0	83.1	80.3	74.7
Market entry	53.2	64.8	77.3	67.7	59.0	55.1	53.2	52.2	50.3	48.3
Volume (million units)										
No market entry	0.14	0.71	0.54	0.62	0.81	0.88	0.93	0.94	0.98	1.05
Market entry	0.11	0.54	0.47	0.59	0.75	0.87	0.92	0.93	0.97	1.00
Operating expense	2.28	4.66	4.76	4.86	4.96	5.06	5.16	5.26	5.36	5.46

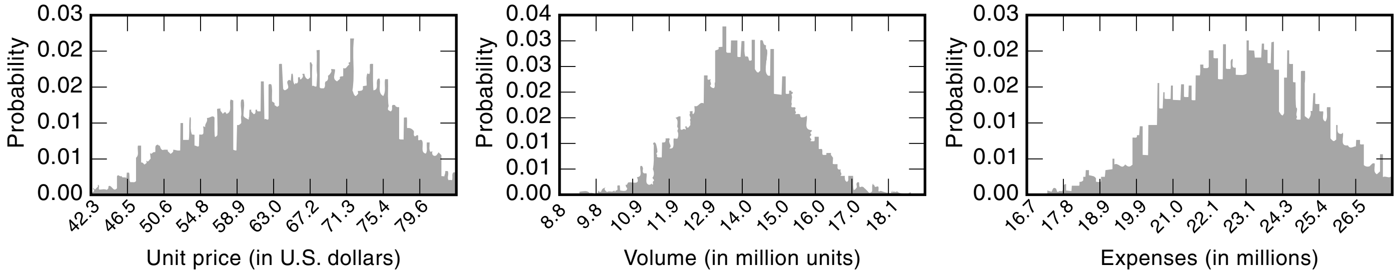


Figure 12. Probability distributions of price, volume, and expenses for the first project year.

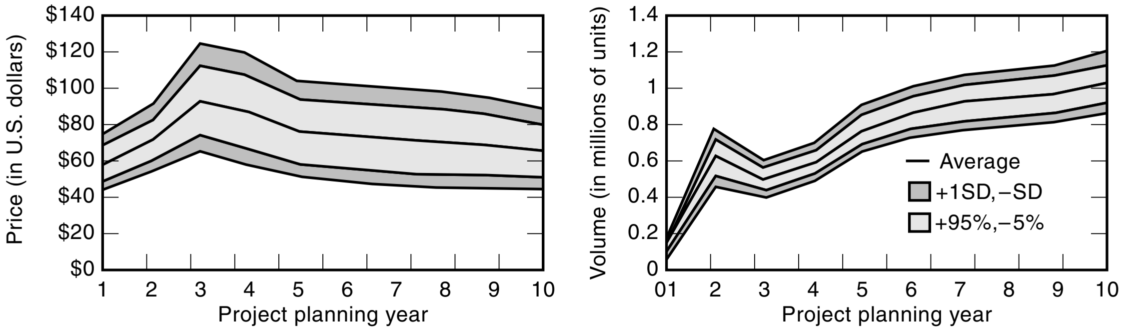


Figure 13. Summary graphs for the service price and volume for the entire project planning horizon. For each year a range of values is shown based on the distributional characteristics of the associated parameter. The range consists of two bands. The lower bound of the inner band is defined by the average value minus one standard deviation, and the upper bound by the average value plus one standard deviation. The outer band is defined by the 5th and 95th percentiles of each distribution.

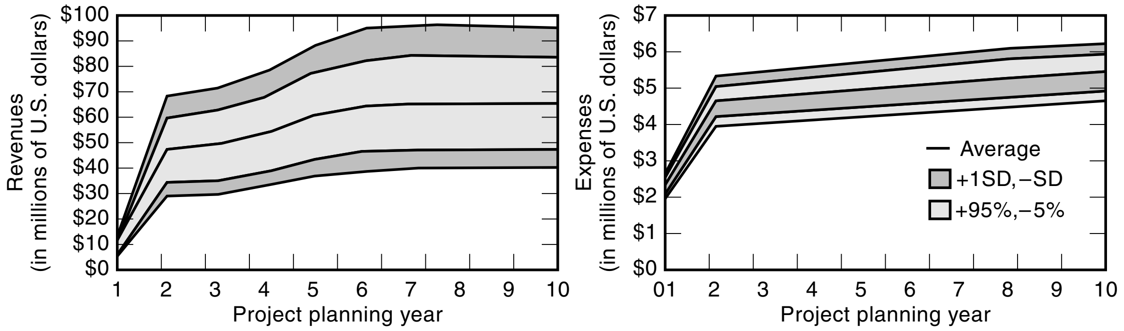


Figure 14. Summary graphs for the project revenues and expenses for the entire project planning horizon. For each year a range of values is shown based on the distributional characteristics of the associated parameter. The range consists of two bands. The lower bound of the inner band is defined by the average value minus one standard deviation, and the upper bound by the average value plus one standard deviation. The outer band is defined by 5th and 95th percentiles of each distribution.

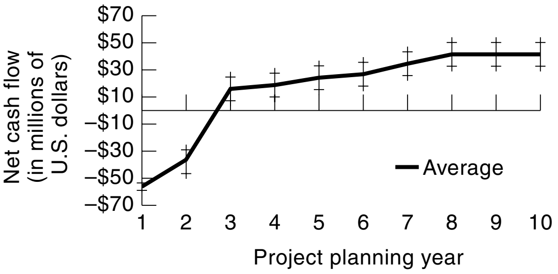


Figure 15. Net cash flow summary.

year planning horizon is 40.9%. Finally, a sensitivity analysis indicates that the most important factor, which influences the project NPV is the probability of a new market entry.

OPTION ANALYSIS AND SIMULATION TECHNIQUES

Traditional project evaluation methodologies assume that all decisions are made using information available at the start of the project. For example, the decision methodology embodied in the net present value computations previously discussed assumes that all relevant information is available when the decision is made to start the project and furthermore that the decision is irreversible. The implication is that project decision-making will not take advantage of new information as it evolves during the life of the project. Project evaluations that require market take-rate projections, for example, will not utilize actual market trends as the project unfolds over time. Certainly this does not reflect actual project management practices. Project decisions are made throughout the life of the project.

The root problem with these traditional methods is the implicit assumption that all decisions are made at the beginning of the project and that the decisions are irreversible. As mentioned before, neither of these assumptions are valid for telecommunications projects. Network deployment plans, for example, will be adjusted to reflect actual network link utilizations. Service offerings will be refined to mirror actual market evolution. Technology decisions may change if new technologies evolve at a faster rate than originally projected.

The option analysis methodology (7) for project evaluation explicitly treats delayed decisions and evolving project information. The methodology has its origins and derives its name from methodologies used to evaluate financial derivative security instruments such as the "put" option contract. These instruments have two sources of value: the ability to delay a portion of the investment decision and the uncertainty in the evolution of the relevant information set. Note that if the information set does not evolve, the financial worth of the instrument is deterministic and thus there is no value associated with the delayed decision.

There are analytical and simulation techniques to evaluate projects with reversible decisions and evolving information sets. The analytic approach is thoroughly described in Ref. 7. These techniques map a project's decision and information structure into comparable financial instruments and use financial analysis techniques for project evaluation. We present and recommend the simulation approach due to the complexity of telecommunications projects and the availability of excellent simulation packages and computing resources.

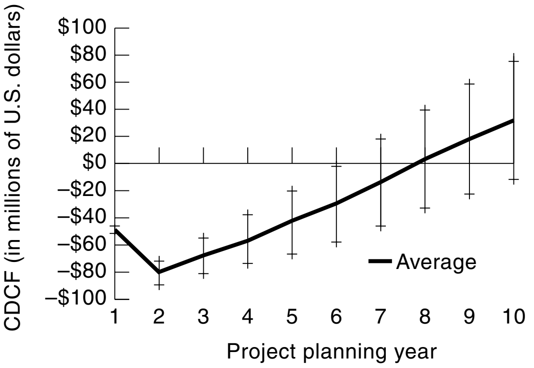


Figure 16. CDCF summary graph.

The analysis is illustrated by expanding the example presented in the previous section. Assume the following additional project information. First, the capital expenditures of $60 million in years 1 and 2 are sufficient to support 1.16×10^6 units of demand (1.05×10^6 plus one standard deviation); that is, $10.34 million investment per 100,000 units. The capital is depreciated over a six-year period and has a market value equal to its book value. Second, the investment of $60 million in year 1 is required to start the business. This will provide for a 5.8×10^5 unit demand. However, the additional $60 million investment will be made only when the previous period demand exceeds 5.0×10^5 units. Third, if demand falls below 75% of expectation during any year the project will be terminated. Fourth, if the per unit revenue falls below 65% of expectation during any year, the project will be terminated. If the project is terminated it is assumed that the accumulated capital equipment will be disposed at book value. Also, project termination will not have any direct exit costs.

Notice that these additional assumptions more realistically reflect actual project decision structure. Capital investment decisions are reversible, perhaps with a penalty. Ongoing project decisions acknowledge the actual evolution of the market. The simulation results for this project example under the additional assumptions just mentioned are displayed in Fig. 17. Recall that Fig. 16 plots the simulation results for the CDCF of the project evaluated with no delayed decisions. Dif-

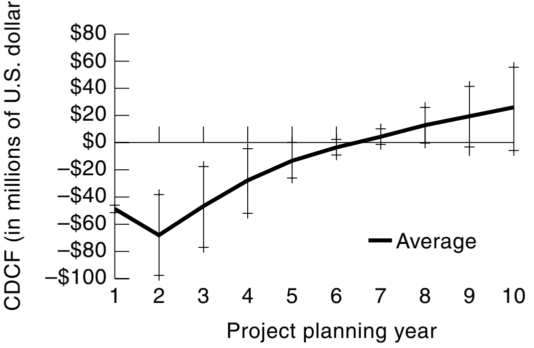


Figure 17. CDCF summary graph assuming project-delayed decisions.

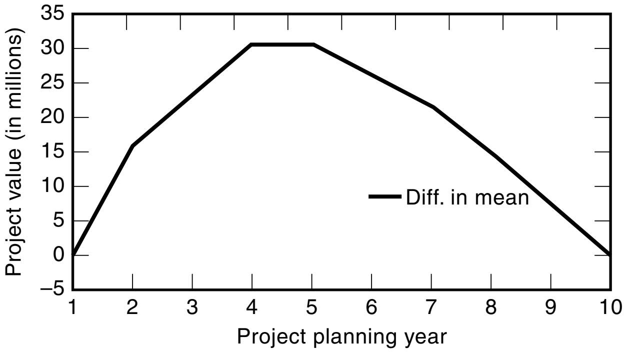


Figure 18. Difference in the mean value of the project, with and without delayed decisions. The expected value of the project at the end of 10 years does not change. This reflects the fact that to get to the 10-year point no terminate decisions are made. The figure indicates that at the end of 4 years the project is expected to have $30M more value by delaying decisions.

ferences between the plots indicate that in the early stages of the project delayed decisions decrease the expected loss. At midstage the project will show positive value sooner by delaying decisions, and in the later stage delayed decisions decrease the variance in the project's value. Figure 18 plots the difference in the mean value of the project with and without delayed decisions. Note that the expected value of the project at the end of ten years does not change. This reflects the fact that to get to the ten-year point no terminate decisions were made. We also note that Fig. 18 indicates that at the end of four years the project is expected to have $30 million more value by delaying decisions.

The general approach to using options analysis methodologies is to construct decision trees (8) that reflect the most likely time-sensitive decision scenario for the project, specify the best distributions for the decision variables, and estimate the financial implications associated with the outcomes. The characteristics of the NPV for the project can then be computed via simulation. Note that all random variables in the project need not be decision variables. Market demand, for example, may be specified as a random variable with associated distribution but may not affect any project decisions. Consider, for example, the case where a desired market image dictates a particular service offering. Even though the market demand should be specified as a random variable for computing the NPV of the project, its actual realization would not be used for project decisions.

The Options Analysis methodology is defined as follows, using the notation introduced in the preceding section. Define I_0 as the information set available at project time zero and $I_n = I_{n-1} \cup$ {time-n information}. The expressions for the NPV average value E(NPV) and variance Var(NPV), are then given by the following expressions:

$$E(\text{NPV}) = \sum_{n=0}^{N} \frac{E(\text{CF}_n|I_n)}{(1+k)^n}, \qquad \text{Var}(\text{NPV}) = \sum_{n=0}^{N} \frac{\text{Var}(\text{CF}_n|I_n)}{(1+k)^{2n}}$$

Also, as in the preceding section, a similar expression for covariance using time-dependent information can be written.

Finally, it is important to note that this analysis does not assume that additional information is available at time zero. It simply acknowledges that fact that information will evolve over time and that decisions will be made using most curent information.

SUMMARY

A discussion of economic issues associated with telecommunications engineering problems has been presented. The focus is to understand the overall economic context of engineering projects and to present an approach for decision-making using sound financial analysis techniques. Project uncertainties are dealt with systematically, and results use standard financial measures to facilitate the decision-making process.

BIBLIOGRAPHY

1. M. E. Porter, *Competitive Strategy, Techniques for Analyzing Industries and Competitors,* New York: Free Press, 1980.
2. A. Grove, *Only the Paranoid Survive,* New York: Bantam Doubleday Dell Publishing, 1996.
3. E. Drakopoulos, *Computer Communications,* Amsterdam, The Netherlands: Elsevier Science, 1998.
4. D. Besanko, D. Dranove, and M. Shanley, *Economics of Strategy,* New York: Wiley, 1996.
5. F. Zettelmeyer and P. Stoneman, Testing alternative models of new product diffusion, *Econ. Innov. New Technol.,* **2**: 283–308, 1993.
6. C. S. Park and G. P. Sharp-Bette, *Advanced Engineering Economics,* New York: Wiley, 1990.
7. A. K. Dixit and R. S. Pindyck, *Investment Under Uncertainty,* Princeton, NJ: Princeton University Press, 1994.
8. J. L. Riggs, D. D. Bedworth, and S. U. Randhawa, *Engineering Economics,* New York: McGraw-Hill, 1996.

ELIAS DRAKOPOULOS
MATT MERGES
Lucent Technologies