ENGINEERING ECONOMICS

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Contents

Summary

Engineering Economics is the application of economic principles to the evaluation of engineering design and the selection of technical alternatives in engineering projects. Key decision making tools for evaluating the economics of engineering projects were originated by two 19th century professional engineers: Arthur Wellington in the railroad industry and Jules Dupuis in public sector civil engineering projects. Their original works have been extended and augmented over the years by engineers and economists and are widely applied today to justify the financial and economic efficacy of engineering projects.

Engineers apply science and technology in designing products and processes. Through innovation, research and development, and engineering design, an array of new technologies become available to society over time. Some of these technologies will be used and some will not. Understanding the economic characteristics of a technology and its costs is what distinguishes engineering economics from other branches of economics and finance.

Engineers working in the private economy select the combination of product designs, fabrication materials, and manufacturing process technologies that will minimize cost while achieving the desired product quality and price necessary to insure the anticipated product demand. Through this process of cost minimization, profits are maximized and the economic decision making process is consistent with the firm's fiduciary responsibility of providing maximum financial return to the stockholder. Engineers working in the public sector are faced with a more complex situation. They are usually required to account for the benefits that will accrue to the community as a whole as a

result of the proposed project. They must also account for social costs, such as environmental damage, that may occur as a result of undertaking the proposed project. This commonly occurs in the work of civil engineers. This chapter describes the problems faced by engineers making economic decisions in private industry and in the public sector and illustrates the analytical frameworks used.

1. Introduction - Engineering, Economics and Society

The engineer is a designer and a builder. The engineer applies science and technology in order to design products and systems that are useful to society. Typical examples are the design of a new machine, the selection of a technology for the design of a manufacturing process, the design of a system to capture usable energy from a natural energy source, and the design of an algorithm for a software product.

Usually engineers work for industrial firms and the firms wish to sell these designs, products, and technical solutions to their customers. The firm is the institutional linkage between the problem solving done by the engineers and having it fulfill social needs through the mechanism of the marketplace. This leads us to a general definition of engineering. *An engineer is a person who applies science and technology in designing products and processes to address social needs*. It is the last part of this definition, "…to address social needs" that links engineering to economics.

Economics is often defined simply as *the study of how humans use scarce resources to produce various commodities and distribute them to members of the society for their consumption*. The engineer is a primary actor in finding the best way to "…use scarce resources to produce various commodities…" In particular it is the engineers' goal to use resources of lesser economic value in order to produce products and systems of greater economic value.

Neoclassical economists have shown that the only observable measure of "value" is price. The price (value) of a commodity or a product results from the interaction of supply and demand for that commodity. The marketplace distributes resources and goods based on the "implied social value" indicated by the price. Engineers, through design and manufacture, convert commodities and resources of lower price (value) to products of higher price (value). Thus, for example, silicon (sand) is transformed through manufacturing processes to obtain a computer chip, which is worth much more than the input material (sand) and the power consumption and machinery usage that goes into producing it. If an engineering design converts resources and commodities of higher value into a product or system of lower value, it is a failure of engineering.

Engineering economics is closely linked to the underlying principles of microeconomics. Microeconomics is *the study of economic units, such as firms, households, and consumers determining value through buying and selling in the marketplace*. The "market" is the arbiter of value through its price setting role and the engineer must respect price signals to ensure that the proposed design or manufacturing process provides an increase in value to the society. When the engineer is working outside of the normal influence of the marketplace, it is more difficult to objectively judge his or her success. For example, engineers work in the public sector on infrastructure programs, in military contractor industries, and for government labs. In these cases there is no social marketplace for buying and selling the new designs and products. In the public sector, the output of the engineer's work may be a specification for a public transportation system, a levee or water control system, or a fighter aircraft, among others. There is no readily available market pricing to determine the value of the output. Contrast this with designing and building a new oil drilling platform. In this latter case the value of the design can be estimated directly from the price of oil and the increase in yield or higher pumping rate of the new design. It is more difficult to assess the economic value that flows from the public transportation system (will the public use it?) or the effectiveness of a new fighter aircraft design (what is its value to society?). In effect, it is more difficult for the engineer to know that the output of his/her effort will be of greater social value than the input. In these cases the practicing engineer will focus on the *minimal cost* safe design that achieves the functional specifications of the product or system. When possible, engineers and government planners may attempt to estimate the social benefit using artificial, market-like pricing schemes. These will be discussed later in Section 4.

The process of converting inputs to outputs just described is not simply a matter of assembling resources and combining them in known ways to create an output. Engineers, along with their physics and mathematics colleagues, are engaged in creating entirely new innovations through the process of research and development – a process that leads to what is called "technical change." Technology is broadly defined as *society's sum total of knowledge about the industrial arts*. This is a rather vague definition since technology is not easy to measure using this definition. Technical change, on the other hand, *refers to an increase in the pool of technologies that are being used by industry*. This is easier to observe empirically. The existence of technology does not insure its adoption by industry. Technical change takes technology from the knowledge or prototype stage into the economic arena. *If the pricing mechanism of the marketplace and the investment decision processes are working properly, a new technology will be used only if it is economic to do so*.

A concept related to technical change is "productivity." Industrial productivity is a measure of the ratio of physical output produced to physical input used by a company or industry. The most common measure of industrial productivity is labor productivity, or output per employee hour. A high rate of labor productivity is associated with an economy that produces more physical product per capita, or wealth per person, for the members of its society. In fact, the primary way that an industrial or agricultural economy can increase the aggregate level of wealth for its citizens is by increasing aggregate productivity.

High rates of industrial productivity are associated with high rates of technical change. Several studies by economists have tried to measure the underlying forces that increase industrial productivity, measured as output per worker-hour. They have found that increases in industrial productivity cannot be accounted for simply by the substitution of more capital equipment for labor (referred to as "capital deepening"). Researchers have found that a major part of the improvement in productivity comes from innovations in methods of production and the "quality" of capital goods, generally referred to as "technical change" (Solow, 1957; Boucher, 1981). This process of technical change is not a linear process and it is subject at all points along the way to an economic test, which is administered by engineers and managers working in their particular industries. An example of the complexity of technical change and its relationship to productivity is illustrated in Box 1a.

Box 1a illustrates many aspects of how technical change works its way through the economy. A new material which was invented for the light bulb industry in Germany in the 1920s, tungsten-carbide, was adapted in a novel alloy, tungsten-titanium carbide, for the design of cutting tools that could replace high speed steel in metalworking. The new material was thought to be capable of cutting metals at much higher speeds than existing cutting tools. However, these cutting tools would not be very productive when used in existing machinery due to the inability to operate the existing machines at higher speeds while maintaining tolerance precision. This led to new machine designs with the capability of running two to three times as fast as existing machines without vibration. These machines started to become available in the 1940s and were adopted widely by industry following World War II. Subsequently, throughout the 1950s and 60s, the rate of productivity in metalworking industries rose mostly due to technical change, which began with the development of tungsten-carbide material in the 1920s. At each step in the process described in Box 1a, there is an opportunity for an economic assessment of an investment. The metallurgists and technical mangers working for Osram, the German light bulb company, had to consider the investment of R&D resources and the likelihood of a successful outcome in trying to replace diamond drawing tools with a new, less expensive material. When Phillip McKenna created an alloy of tungsten carbide that could machine metals at high speeds, the potential market for this new technology had to be evaluated before launching a new company based on it. Similarly, machine tool builders had to assess the economics of redesigning their equipment to accommodate the new cutting tool technology. Finally, engineers in the metalworking industry (fabricated metal products, transportation equipment, machinery manufacture, and instruments) were responsible for computing the economic advantage of replacing existing production equipment with these newer machines. From research and development, through product design, through adoption of new technology in manufacturing processes, economics plays a key role in the decision process. Along this continuum there are engineers, scientists and technical mangers who must address the economics of these decisions. This is the fundamental purpose of engineering economics. It should be pointed out that increasing productivity is not the direct objective of the engineering economic decision process. It is a *derived effect*. The engineering economic decision process will substitute newer technologies for older technologies *only when the former can be justified economically*. For example, a computer controlled machine tool will displace a semi-automatic machine tool only if it is more cost effective for the given application. As newer, more efficient technologies prove themselves economically and displace older equipment, output will naturally increase in relation to the amount of labor used, thus creating an increase in labor productivity. The increase in productivity is a *derived effect* from the economic decision-making process that chooses among technological alternatives based on the criterion of the minimization of combined capital and operating costs. This is the decision making process governed by the principles of engineering economics. The origins and methods of this decision making process will be described in Section 2.

In the early 1920s the German electrical bulb company, Osram, looked for alternatives to the expensive diamond drawing dies used in the production of tungsten filament wire for electric bulbs. Their work led to the invention of cemented carbide, also called tungsten carbide (WC), which could be used in applications where wear resistance was important. However, cemented carbides were relatively ineffective in high speed machining of steel components. Soon thereafter, an American scientist, entrepreneur and engineer, Phillip McKenna, invented a tungsten-titanium carbide alloy (WTiC2) for cutting tools that provided a productivity breakthrough in machining of metals. In 1938 he founded the Kennametal Corporation in Latrobe, Pennsylvania, USA and began producing tooling that could be used in metalworking facilities from automobiles to fabricated metal products to the production of machinery, itself. In 1955 the American Society of Tool Engineers presented him with its Engineering Citation of the year for "…the advancement of science and the public welfare." In Table B1.1, comparisons are made between carbide tooling and its predecessor, high speed steel, on cutting speed performance.

Table B1.1 Comparison of Carbide and High Speed Steel Cutting Speeds

	Cutting Speed, fpm	
Work Material	**High Speed Steel**	**Carbide**
B1112 steel	225	550
1020 steel	180	500
Brass	250	725
Aluminum alloys	300	400
Magnesium alloys	300	700

Source: *Materials and Processes in Manufacturing*, 4th Ed. E.P. DeGarmo, Macmillan Publishing Co., 1974.

In order to take complete advantage of this new tooling technology, the structural characteristics of the machines required redesign. The ability to perform work at higher speeds and feeds required greater horsepower and more rigid machine construction. In other words, a new generation of machinery had to be designed, built and put into production in order to fully utilize the new tooling technology. Some illustrative statistics on the changing specification of lathes during the period are shown in Table B1.2.

Table B1.2 Construction and Performance Characteristics of Lathes

	1938	**1948**	**1958**
16-inch engine lathe:			
Horsepower	7.5 hp	10.0 hp	20.0 hp
Metal removal rate	16 cu in/min	20 cu in/min	40 cu in/min
RAM-type turret lathe,	-	-	-

1.5-inch round stock:			
Horsepower	7.5 hp	10.0 hp	25.0 hp
Weight	3850 lb	4500 lb	5750 lb
Speed	730 rpm	1460 rpm	2000rpm

Source: *American Machinist*, October 20, 1958.

Box 1a. Technical Change in Carbide Tooling and Machine Tool Productivity

American Machinist magazine estimated that less than ten percent of the stock of machine tools that existed in 1948 was of current design. Ninety percent were of pre World War II design. The period following World War II saw massive capital investment by the industries that use machine tools in their manufacturing processes (metalworking industries). Table B1a.3 shows the average age of the machine tool stock in those industries for two sub-periods, 1955-65 and 1965-73. This represents a considerable increase in the stock of new designs from 1948. The table also shows the rates of increase in output per worker-hour during the same sub-periods as the new technology was adopted by the engineers in the metalworking industry. Using an econometric model to estimate the amount of productivity improvement arising from capital deepening and the amount of productivity improvement arising from technical change, the estimates in the last two rows of Table B1a.3 were made. The conclusion is that the tungsten-titanium carbide technology and the technical change introduced by using the material in cutting tools and redesigning the machine tools to accommodate the new tooling were the primary factors in the rate of productivity advance. In effect, technical change was the main contributor to productivity growth of the metalworking industries during these periods.

Table B1a.3 Plant Modernization and Productivity in Metalworking Industries

	1955-1965	***1965-1973***
Percent of machine tool stock		
Less than 10-years old	40	36
More than 20-years old	18	23
Annual rate of productivity growth in metalworking industries		
Total annual productivity growth (percent)	2.6	2.2
Productivity growth rate from capital deepening	0.6	1.0
Productivity growth rate from technical change	2.0	1.2

Source: Boucher, 1981.

Box 1b (Box 1a. continued). Technical Change in Carbide Tooling and Machine Tool Productivity

2. Principles of Engineering Project Evaluation

Engineering Economics is the application of economic principles to the evaluation of engineering design and the selection of technical alternatives in engineering projects. From the previous section one can see that there are many aspects of engineering that benefit from economic analysis. The field of engineering economics began with a focus on capital equipment investment evaluation, which is the last step of the process described in Box 1a. The journal of the profession, *The Engineering Economist*, declares itself to be “a journal devoted to the problems of capital investment.” However, over time the issues addressed by the journal have evolved to include research & development, engineering design economics, decision theory, and public policy analysis as it affects the investment decisions made by engineers. The discipline has its origin in the railroad industry of the 19th century. A prominent railroad engineer, Arthur Wellington, proposed a method of economic reasoning for the justification of building new railway properties. Up to that time, industrial firms did not measure the relationship between the capital invested in a project and the earnings that the project generated. Wellington believed that the proper relationship between capital investment and earnings should include an adjustment for the point in time at which the investment is made and the receipts occurred. He proposed the Present Value (PV) concept for project justification, which he also referred to as “present justifiable expenditure,” which has since become the foundation of corporate capital budgeting. See Box 2 for Wellington’s views on engineering and capital investment.

Box 2. Wellington on Engineering and Economic Evaluation

“… the [railway] locating engineer has but one end before him to justify his existence as such – to get the most value for a dollar which nature permits … His true function and excuse for being an engineer, as distinguished from a skilled workman, begins and ends in comprehending and striking a just balance between topological possibilities, first cost, and future revenues and operating expenses.”

“In other words, reduction of first cost [initial construction costs] to the lowest possible point is, in logical or economic order, the first consideration … It does not mean or imply cheap and shabby construction. It simply means an avoidance of waste, either in saving money or spending it. It simply means a recognition of the fact that every dollar and every day’s work which goes into the ground and does not bring something out of it, makes not only the individual but the whole community the poorer.”

Wellington tabulated first cost expenditures that justify reducing future costs or gaining future income at various rates of interest on borrowed funds to finance the first cost. A portion of one such table follows.

Table B2. (Partial) Showing the Justifiable Present Expenditure to save $1 per annum for various Terms of Years at various Rates per Cent for Capital.

Term Of Years	Justifiable Present Expenditure with Interest at -							
	3 percent	4 percent	5 percent	6 percent	7 percent	8 percent	9 percent	10 percent
1	$0.97	$0.96	$0.95	$0.94	$0.93	$0.93	$0.92	$0.91
2	1.91	1.89	1.86	1.83	1.81	1.78	1.76	1.74
3	2.83	2.78	2.72	2.67	2.62	2.58	2.53	2.49
4	3.72	3.63	3.55	3.47	3.39	3.31	3.24	3.17
5	4.58	4.45	4.33	4.21	4.10	3.99	3.89	3.79
6	5.42	5.24	5.08	4.92	4.77	4.62	4.49	4.36
7	6.23	6.00	5.79	5.58	5.39	5.21	5.03	4.87
8	7.02	6.73	6.46	6.21	5.97	5.75	5.53	5.34
9	7.79	7.44	7.11	6.80	6.52	6.25	6.00	5.76
10	8.53	8.11	7.72	7.36	7.02	6.71	6.42	6.14

Source: Wellington, 1911.

Box 2. Wellington on Engineering and Economic Evaluation

In Wellington's Table B2 of Box 2, he computes the amount of money that an engineer should be willing to invest at the beginning of a project (called "Present Expenditure" or "First Cost") in order to save operating expenditures of $1 each year, or increase income of $1 each year, for a specific number of years and at a specific interest rate for the borrowed money. So, from Table B2, it is justified to invest $4.21 in engineering improvements that will reduce costs (provide additional savings) of $1.00 per year for five years when the investment funds are borrowed at 6%. This is true because the five years of savings will completely pay back the original loan plus all the interest on the loan at 6%. The computations are shown in Table 1.

[1]	[2]	[3]=[2]x0.06	[4]	[5]=[2]+[3]-[4]
Year	Outstanding Loan (beginning of year)	Cost of Interest during year at 6%	Income or cost savings	Outstanding Loan (end of year)
1	**$4.21**	$0.2526	$1.00	$3.4626
2	3.4626	0.2078	1.00	2.6704
3	2.6704	0.1602	1.00	1.8306
4	1.8306	0.1098	1.00	0.9404
5	0.9404	0.0564	1.00	**0**

Table 1. Demonstration of Wellington's Table B2 for 6% and 5 Years.

Wellington's work was advanced in the early 20th century by two Stanford professors, John Fish (Fish, 1915) and Eugene Grant (Grant, 1930). Fish was the first to introduce the cash flow diagram, which is widely used to illustrate the relationships of the flow of money in a project at different points in time. Figure 1 is such a diagram to illustrate the situation of Table 1 in which $4.21 is invested as first cost and $1 is returned at the end of each subsequent year. Investments (capital expenditures) are shown as down arrows (negative amounts) and savings or incomes are shown as up arrows (positive flows).

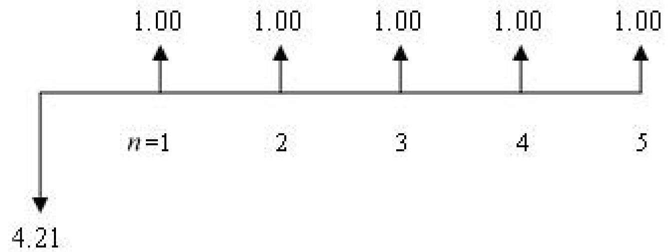

Figure 1. Cash Flow Diagram

Based on Table 1, we know that the value of all the savings will repay the borrowing of $4.21, including the interest payments at 6% over five years. This fact can be computed from the cash flow diagram using the Present Value (PV) formula, also introduced by Wellington:

$$PV = \sum_{n=1}^{N} \frac{X_n}{(1+r)^n} = \sum_{n=1}^{5} \frac{\$1}{(1+0.06)^n} = \$4.21 \qquad (1)$$

X_n = cash flow in period n.
r = rate of interest on borrowed funds.
n = year of cash flow.
N = number of years in the cash flow time horizon.

So, from Formula (1), borrowing a sum of \$4.21 at 6% and investing it at $n = 0$ is economically justified because the savings from the reduced cost will pay back the borrowed funds plus the interest due on the loan. Taking the argument one step further, we define the Net Present Value (NPV) as the value of the Present Value (PV) of the savings minus the first cost.

$$NPV = \sum_{n=1}^{N} \frac{X_n}{(1+r)^n} - First\,Cost = \sum_{n=1}^{5} \frac{\$1}{(1+0.06)^n} - 4.21 = 0 \qquad (2)$$

When the NPV is zero, the monetary gains from the investment exactly equals the initial investment (borrowed funds) and the interest charges on the borrowed funds for the investment.

This example can also be interpreted more generally by proposing that an engineering project exists in which we can invest \$4.21 of technical improvements in a project for each \$1 gained in cost savings over the next five years. An example could be an energy saving technology, such as improved thermal insulation, that saves \$1 per year over 5 years for each \$4.21 invested. When stated in this way, the \$4.21 is the cost of the investment and is independent of how the project is financed. It turns out that if we finance the project at 6%, the NPV is zero and the project is exactly justified. What if we borrowed the capital at 5% instead of 6%? For this case the NPV is

$$NPV = \sum_{n=1}^{N} \frac{X_n}{(1+r)^n} - First\,Cost = \sum_{n=1}^{5} \frac{\$1}{(1+0.05)^n} - 4.21 = 0.119$$

Because the borrowing was done at 5% instead of 6% there was less interest to pay and the returns from the investment exceeded the first cost plus interest payments. The remainder (positive NPV) is an extra monetary gain over the justifiable present expenditure. Thus, a zero or positive NPV indicates a justifiable investment and a negative NPV indicates an investment that is not justifiable because the monetary gain from the project will not cover the combined investment cost and the interest on the borrowed funds used to finance the project. *The NPV criterion is the basic criterion of project acceptance, which was first proposed as a criterion for corporate project investment analysis in the early years of engineering economics.*

Discounting future payments by the rate of interest has a long history in the financial industries, such as bond trading. Wellington was the first person to apply the concept to corporate investments in physical assets. Despite the efforts of Wellington and other early pioneers of engineering economics, the NPV criterion was not widely adopted by industry at the time. One exception was the American Telephone and Telegraph Company (AT&T), which was largely managed and run by engineers and scientists. AT&T had to evaluate technical projects with expected lives of twenty years or more.

These included laying large networks of underground cables and investing in large centralized switching systems. The present value method was very appealing for evaluating the allocation of capital over long time horizons. By 1926 AT&T and Western Electric, its manufacturing division, had developed standard procedures for evaluating capital investment projects, which included the application of the present value method. The previously mentioned Stanford engineering professor, Eugene Grant, was a regular visitor to AT&T headquarters in New York City while completing his master's degree in economics at Columbia University in 1927-28. Early collaborations between academics and industry were an impetus to the continued development of the discipline of engineering economics.

In the following sections we will discuss various components of the net present value formula. The following equation for net present value will be used.

$$NPV = \sum_{n=0}^{N}\left[\frac{X_n}{(1+r)^n}\right] , \qquad (3)$$

where

NPV = net present value
X_n = cash flow in period n
r = a discount rate based on the financing cost of the project
N = number of years or periods of the project
n = an index of time

The value of X_n can be the amount of money invested in the project (negative value), or an amount of monetary benefit being realized from the project (positive value), or a monetary expense, such as an annual maintenance cost (negative value). Formula (3) nets out those positive and negative monetary benefits and costs and also weights them using the discount factor depending on the year that they were incurred and the financing discount rate. As n increases, the denominator of Formula (3) increases and the discounted magnitude of X_n is reduced. As long as the final calculation of Formula (3) is a value greater than or equal to zero, the project is justified. If the value is negative, the project is not justified. There are two components of Formula (3) to discuss. The first is the meaning of the discount rate, r; the second is the composition of X_n.

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Biographical Sketch

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