3 Economic modeling

3.1 Objectives

Process and systems costs often play a major role in the implementation of both processes and environmental solutions. Though this might be a bit depressing, costs and economics often play the major role in deciding whether to implement solutions that improve energy efficiency or sustainability or both. In other words, solutions will not be adopted if they are not worth it, whether they are beneficial to the planet. What this also means is that one can influence whether solutions are chosen by imposing costs (negative or positive) through subsidies taxes, tariffs, permits, tax breaks etc. This is the basis of many energy and environmental policies.

For all these reasons, it is essential for you to understand how to estimate the cost of a process or system of processes. To do so, we will cover three topics: (1) capital cost estimation, where you will learn how to estimate the cost of a capital investment (i.e. the investment needed to build a physical asset); (2) operating costs, where we will discuss costs that occur regularly over the lifetime of the process (which importantly will include a discussion of externalities—a cost or benefit that concerns an uninvolved third party as is the case for environmental damages); and finally, we will discuss (3) the time value of money. All the aforementioned expenses occur at different times: sometimes many years apart. As we will discuss, the value of money is very different depending on when you must spend it. We will cover how you can compare these costs across time periods using discounting techniques. This approach also allows you to calculate the true value of an investment.

3.2 Capital cost estimation

The goal of this section is to learn how to estimate the investment cost of a physical asset that is needed to run a process or system. This is generally an equipment. The easiest starting point is the known cost of a similar piece of equipment. However, this corresponding piece of equipment, for which a price is known, will frequently be of a different capacity than the one that is desired for the system of interest. In such cases, a well known formula is used to adjust for capacity:

$$C_{\mathrm{Q}} = C_{\mathrm{B}} \left(\frac{Q}{Q_B}\right)^M \qquad (3.1)$$

With:

C_{Q}: the known equipment cost at the capacity Q of interest.

C_B: Equipment cost at the base capacity (at which the price is known)

Q_B : The base capacity (at which the price is known)

M: An equipment-dependent exponent

The value of the exponent is crucial as a value below 1 will lead to a decrease of normalized investment cost (i.e. investment per item/quantity produced) with increasing capacity. This relation illustrates where “economies of scale” intervene. An average of 0.6 is usually taken across industries—this is referred to as the $6/10^{\mathrm{th}}$ rule. Values of 0.8-0.9 can be used to processes that used a lot of gas compression or mechanical handling where scaling offers less benefits (this is the case for methanol, plants or pulp and paper processes). Petrochemical processes have traditionally seen values of M around 0.7. Where highly instrumented processes (e.g. processes that require a lot of complex controls) lead to values of 0.4-0.5 because a bigger process does not drastically increase the cost of instruments.

Frequently the cost of a piece of equipment is known for a given year that is different from the year when the investment estimate is needed (usually the present) and equipment costs can vary quite a bit over time. For this reason, relations exist to account for price evolution and correct for the age of the cost data:

$$C_i = C_j \left(\frac{Index_i}{Index_j}\right) \tag{3.2}$$

With:

C_i: Equipment cost in year *i*.

C_j: Equipment cost in year *j*.

$Index_i$: Cost index[1] in year *i*.

$Index_j$: Cost index in year *j*.

Once the equipment cost is estimated for the right capacity and the right year, additional corrections can be made to equation 3.1 if the equipment is to be used using different conditions than those used in the base case:

$$C_{\text{Q,corr}} = C_{\text{B}} \left(\frac{Q}{Q_B}\right)^M f_M f_P f_T \tag{3.3}$$

With:

f_M: Material correction factor.

f_P: Design pressure correction factor.

f_T : Design pressure correction factor.

Typical values are given in the Tables below (Table 3.1):

[1] Common price indexes for chemical processes include the Marshall and Swift Indexes (published in *C&E News*), and the Nelson-Farrar Cost Index (published in the *Oil and Gas Journal*).

Material	Correction factor f_M
Carbon steel	1.0
Alum	1.3
Stainl	2.4
Stainl	3.4
Haste	3.6
Mone	4.1
Nicke	4.4
Titani	5.8

Design temperature (°C)	Correction factor f_T
0–100	1.0
300	1.6
500	2.1

Design pressure (bar absolute)	Correction factor f_P
0.01	2.0
0.1	1.3
0.5 to 7	1.0
50	1.5
100	1.9

Table 3.1. Correction factors for different process materials, pressures and temperatures (from *Smith*, 2005).

Once you know the cost of the individual pieces of equipment, you still have to estimate the full cost of installing the process/system. This can be done with the following equation:

$$C_{\text{Total}} = \sum_i C_{Q,i}[f_M f_P f_T(1 + f_{PIP})]_i + \begin{pmatrix} f_{ER} + f_{INST} + f_{ELEC} + f_{UTIL} + f_{OS} \\ + f_{BUILD} + f_{SP} + f_{DEC} + f_{CONT} + f_{WS} \end{pmatrix} \sum_i C_{Q,i} \tag{3.4}$$

This calculation of the total fixed capital cost (C_{Total}) includes a first contribution of piping (f_{PIP}) that is proportional to the corrected cost of equipment ($C_{\text{Q,corr}}$) and a number of other correction factors that are proportional to the cost of uncorrected equipment (see Table 3.4).

Finally, a working capital that is usually estimated as being 15% of all fixed capital costs is added to account for start-up costs of the process, purchasing the initial raw materials, building product inventory, spare parts, having cash on hand etc. This capital is notably used to start the process and bridge the time until the first product is sold. This leads to a total investment (I_{total}) of:

$$I_{total} = 1.15 * C_{\text{Total}} \tag{3.5}$$

3.2 Operating cost estimation

To estimate operating costs, one must add up the typical costs required day to day to run the system or process. These costs will include the categories listed below.

Raw material costs (RM). Raw materials include common inputs and consumables that are required to run the process. Typical materials include chemicals, materials or catalysts. You can get current estimates from commercial sources such as the Chemical Marketing reporter, European Chemical News, Asia Chemical News, etc. An attractive free source of information is Alibaba.com where you can search for offers of various chemicals. I recommend taking the average of multiple offers for fairly large amounts (e.g. > 1 ton) to get a true idea of what a large quantity of material costs. All of these costs are variable and can fluctuate with the market and so can be a significant source of uncertainty.

Utility costs (U). Utilities usually contain all costs associated with process energetics. These include fuel, electricity, steam, cooling water, refrigeration costs, compressed air, etc. Electricity and fuel costs can be looked up on public markets. Cooling water is usually cheap (but never free), especially if plants are installed close to rivers and can thus often be neglected in overall cost calculations.

Taxes (T). Here, we are separating taxes on corporate profits from environmental taxes (which we discuss below). Profit taxes are generally levied on gross profits (P, which are sales or revenue minus production expenses) to which allowances or deductions (D) are subtracted:

$$T = (P - D)t_R \tag{3.6}$$

Where t_R is the tax rate. The most common deduction is typically equipment depreciation, which is generally obtained by distributing the equipment cost equally over the course of its lifetime (at the end of which it is fully depreciated and worth zero).

Operating labor. Operating labor is the labor needed to run the equipment it can be estimated, depending on the process using Figure 3.1.

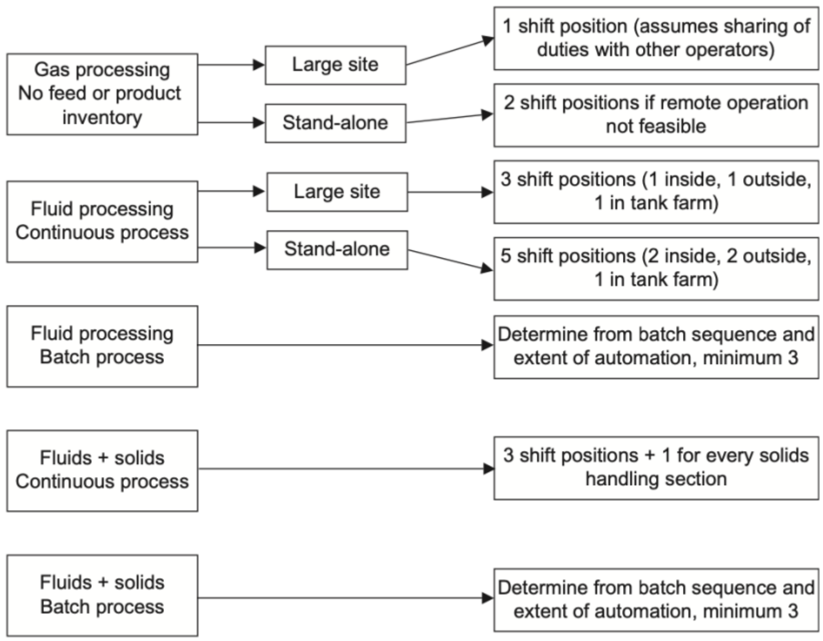

Fig. 3.1. Estimated the required labor depending on the process of interest.

A rough estimate for the 1 shift position is usually about 60-70 k€ a year. Other fixed costs are often associated with labor. One of those is supervision (i.e. the people you need to supervise those performing the direct labor on the machines), which is assumed to be proportional to labor ($Supervision \approx 0.25\, L$). Another is overhead, which accounts for the costs of having the laborers, supervisors and running the plant that are not directly associated with the equipment. It could be electricity for the offices, laptops for the workers, social contributions, etc. This is typically estimated as $Overhead \approx 0.5\,(L + supervision)$.

Plant costs. Finally there are some miscellaneous costs associated with the plant that include maintenance ($Maintenance \approx 0.02\, C_{\text{Total}}$) and the renting of the land ($Rent\ of\ land \approx 0.02\, C_{\text{Total}}$) which are both proportional to the total fixed capital cost (C_{Total}). Finally, you add the plant overhead, which covers corporate overhead functions such as IT, HR, legal, finance, and R&D costs. Plant overhead is proportional to labor, supervision overhead and maintenance: $Plant\ overhead \approx 0.65\,(L + supervision + overhead + maintenance)$.

Externalities. The definition of an externality in the context of building a technology is an indirect cost or benefit to an uninvolved third party. In the context of energy, they are often used to refer to the cost of environmental damages caused by the technology (i.e. a negative externality). In the context of chemical or energy-related processes, the term externality is often used to refer to the cost of environmental damages linked to the technology (i.e. a negative externality), which if unaddressed, are largely born by society.

There are essentially two ways of dealing with externalities:

- You can pay for the damages. A company/state pays to fix the problem. A typical (though not so successful= example of this is the "superfund" system in the USA where an excise tax (tax at the moment of manufacture rather than at sale) was levied on petroleum and chemical companies to contribute to a superfund, which was then used to clean up environmental disasters. I describe it as unsuccessful because the tax was not renewed due notably to pressure from oil companies in the US and so the fund is now largely empty.
- You can impose an upfront tax (also known as a "Pigouvian tax) that will provide funds to an external entity (usually a government) to deal with the damages. The

taxes usually also provide a major incentive to avoid causing the damaging behavior. Think of green house gas (GHG) taxes that are there to encourage companies and other actors to avoid emitting GHGs. The tax is fairly straightforward (though not always) and may look like:

$$GHG\ tax = Emissions_{CO_{2,Eq}}\ €/ton_{CO_2} \tag{3.7}$$

With all of this put together, we arrive at a total cost of:

$$Total\ costs = \sum_i RM_i + \sum_j U_j + T + L + Supervision + Overhead + Maintenance + Rent + Plant\ overhead + SF + GHG\ tax \tag{3.8}$$

During the lifetime of the process, they will be offset by sales or savings (i.e. avoided costs). Savings are quite typical in energy-related projects and investments. Think of improving your house's insulation or installing solar panels. The yearly difference between total costs and sales/savings is known as the yearly cash flow and will hopefully be positive. At the start of the project, these costs or sales/savings are future cash flows (i.e. operating costs or sales/savings typically only start once the plant starts running—or shortly before). The challenge in doing process economics is to compare investment costs that happen before the project starts and the future cash flow of operating costs and sales/savings. To do so, we will have to understand the effect on time and money, which will allow us to compare current and future cash flows.

3.3 Time and money

The difficulty in comparing a cash flow today and future cash flow is that the value of money changes depending on when it is available. The simplest way of putting this is that money now is worth more than money later. The reason is that money can grow over time (any money you save for retirement now is much more valuable than money you might save closer to your retirement because it has much more time to grow). Any money spent now is gone and cannot be used to earn interest in a bank or investment. Money also loses value over time due to inflation. The changing value of money can be accounted for by using a rate of return (i). This return can be used to calculate a future value of money:

$$F = P\ e^{it} \tag{3.9}$$

Where F is the future worth of present cash flow P. i is the internal rate of return defined for continuous compounding, which means we assume that the value of money evolves all the time rather than at discrete periods. t is the time period.

This equation can be reversed to calculate the present value of future cash flows:

$$P = F\ e^{-it} \tag{3.10}$$

Though complex calculations are typically done with continuous compounding, you are probably more familiar with discrete compounding, which occurs at specified periods (e.g. once a year). In such cases, the formula becomes:

$$F = P\ (1 + i_d)^t \tag{3.11}$$

Where i_d is the yearly compounding interest and t is defined in number of years. You can also compound more than once a year by adapting equation 3.11 in the following way:

$$F = P\ \left(1 + \frac{i_d}{n}\right)^{nt} \tag{3.12}$$

Where n is the number of yearly compounding periods. Note that Equation 3.12 simplifies to Equation 3.11 for $n = 1$.

Similarly to the continuous compounding equations, Equation 3.11 can be reversed to calculate the present value P of future cash flows calculated with discrete compounding:

$$P = \frac{F}{(1+i_d)^t} \tag{3.13}$$

You can calculate a continuous compounding interest i_c from the discrete compounding interest i_d :

$$i_c = \ln\left[1 + \frac{i_d}{n}\right]^n \tag{3.14}$$

As you can see, the formula in Equation 3.14 can be used to link Equations 3.9 and 3.11:

$$F = P\ e^{i_c t} = P\ e^{\mathrm{t}\ln[1+i_d]} = P\ e^{\ln[1+i_d]^t} = P[1 + i_d]^t \tag{3.15}$$

Equipped with these definitions, we now have a way to take all the future cash flows of a process (all F_j) and using continuous or discrete compounding bring them back to their net present value:

$$P_T = \sum_j F_j\, e^{-i_c t} \quad \text{or} \quad P_T = \sum_j \frac{F_j}{(1+i_d)^n} \tag{3.16}$$

Where the t in the sum corresponds to the time in years at which F_j occurs. P_T is the net present value of all expenses for a process. This present value of future cash flows can now be directly compared to investments made today.

It is also useful to calculate the annualized rate of expenditures ($\bar{A}$ i.e. the average amount a project cash flow each year). We start with the definition of this rate, which when integrated over time for the total lifetime of the project T leads to the net present value of all expenses (P_T):

$$\int_0^T \bar{A}\, e^{-i_c t}\, dt = P_T \tag{3.17}$$

If we integrate and rearrange, we can calculate $\bar{A}$:

$$\bar{A} = \frac{i_c}{(1-e^{-i_c T})} P_T \tag{3.18}$$

Ultimately, the final goal of all of these relations is usually to calculate one of two things:

1. Rate of return (i_c or i_d) at a viable product price (e.g. what is the rate of return of me installing solar panels on my roof assuming I can sell electricity at a given price). This often allows the comparison of different projects (e.g. installing solar panels vs. investing in the stock market).
2. Minimum selling price of a product. This is the minimum price at which a product can be sold to achieve a given rate of return. This allows you to compare different processes with the same product (e.g. comparing synthetic natural gas produced by gasification vs. anaerobic digestion).

The overall process is shown in Figure 3.2. It consists of first accounting for all your projected cash flows over time (income and expenses) and second bringing all your cash flows to their present value and summing them up for a given rate of return to calculate the net present value of your project P_T. Third, you can change either the internal rate of return or the selling price of your product so that $P_T = 0$. This is generally an iterative process; in other words, you often need an optimization algorithm to solve for either of these values. Getting the internal rate of return or the minimum selling price is usually the major goal of an economic calculation. However, once these are calculated we can also calculate both the levelized annual costs and revenues. This gives us the expected annual inputs and expenses in our cash flow, which is useful for projections. It also allows us to check our calculations as they should cancel out to give $P_T = 0$.

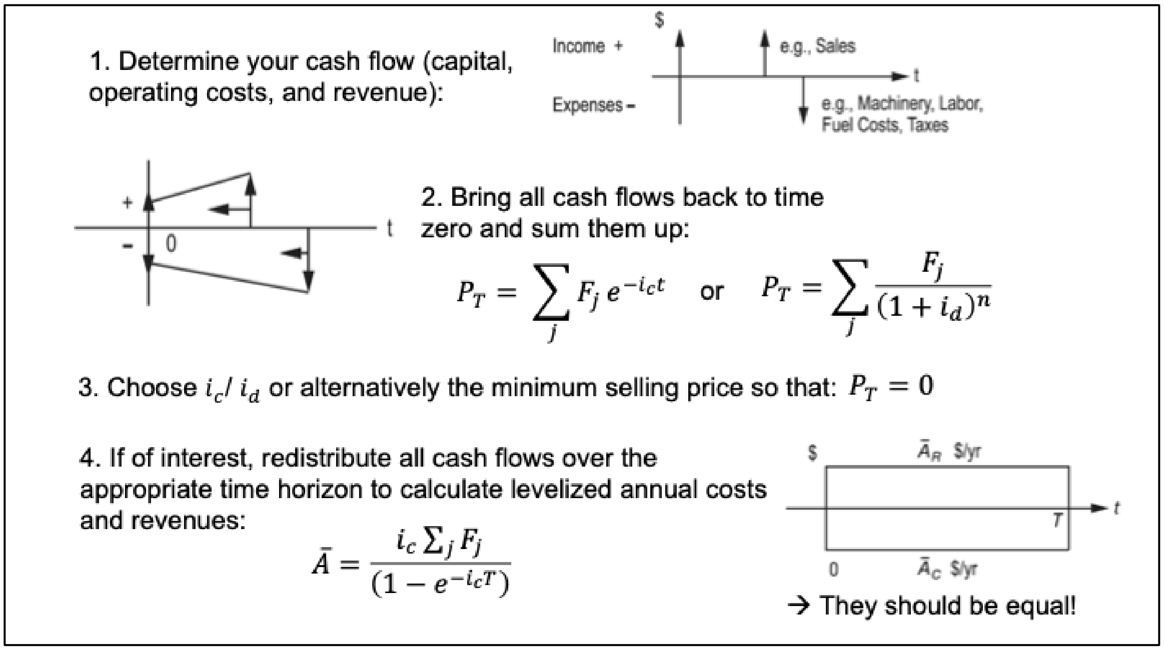

Fig. 3.2. Overall procedure for calculating the project's rate of return (ROI) or the associated product's minimum selling price.

Literature

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