Life Cycle Cost Tutorial

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ABSTRACT

Life cycle costs (LCC) are cradle to grave costs summarized in a three section, three hour tutorial:

1. LCC concepts and applications are described as an overview. Details are provided about how costs are gathered and merged to develop a LCC number usable as a figure of merit. References are provided for additional study—some accounting math is used in this 1.5 hour long section.
2. Failure rate data is used for LCC. Examples show how detailed calculations are prepared and evaluated for developing engineering estimates of LCC in hydrocarbons processing industries—some engineering math is used in this 1.0 hour long section.
3. Uncertainties are considered in preparing LCC values. Direction is provided for use of inexpensive software solutions using DOS and Windows based software programs—some statistics are used in this 0.5 hour long section.

LIFE CYCLE COST DEFINITIONS

Life cycle costs are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during their life. The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives so the least long term cost of ownership is achieved.

LCC analysis helps engineers justify equipment and process selection based on total costs rather than the initial purchase price. Usually the cost of operation, maintenance, and disposal costs exceed all other costs many times over. Life cycle costs are the total costs estimated to be incurred in the design, development, production, operation, maintenance, support, and final disposition of a major system over its anticipated useful life span (DOE 1995). The best balance among cost elements is achieved when the total LCC is minimized (Landers 1996). As with most engineering tools, LCC provides best results when both art and science are merged with good judgment.

INTRODUCTION

Procurement costs are widely used as the primary (and sometimes only) criteria for equipment or system selection. This single purpose criteria is simple to use but often results in bad financial decisions. Procurement costs tell only one part of the story—most frequently the story is so simple, the results may be damaging to the financial well-being of the business enterprise. Often the initial procurement costs, based on simple rules, are so cheap they are not affordable. Simple tools (meaning composed on only one thing) usually give simple results (meaning insubstantial, superficial, and not to be taken seriously). Remember the adage attributed to John Ruston: "It's unwise to pay too much, but it's foolish to spend too little"—this is the operating principle of LCC. End users and suppliers of equipment can use life-cycle costs for:

- **Affordability studies-** measure the impact of a system or project's LCC on long term budgets and operating results.
- **Source selection studies-**compare estimated LCC among competing systems or suppliers of goods and services.
- **Design trade-offs-** influence design aspects of plants and equipment that directly impact LCC.
- **Repair level analysis-**quantify maintenance demands and costs rather than using rules of thumb such as "…maintenance costs ought to be less than _ ? _% of the capital cost of the equipment".
- **Warranty and repair costs-**supplier's of goods and services along with end-users need to understand the cost of early failures in equipment selection and use.
- **Suppliers sales strategies-**can merge specific equipment grades with general operating experience and end-user failure rates using LCC to sell for best benefits rather than just selling on the attributes of low, first cost.

This tutorial is directed toward making LCC understandable and usable by the average engineer. Usually the only value in the life cycle cost equation which is well known and clearly identified is procurement cost—but it's only the tip of the iceberg. Seeing the tip of an iceberg (similar to the obviousness of procurement cost) does not guarantee clear and safe passage around an iceberg. Hidden, underlying, substructures of an iceberg (similar to the bulk of other costs associated with life cycle costing for equipment and systems) contain the hazards.

Life cycle cost was conceived in the mid 1960s when LCC was the subject of considerable interest and publications. Many original works on LCC are now out of print. Publications by Blanchard, et al, regarding life-cycle costs are now sources for a variety of LCC interest:

- **Maintainability** (Blanchard 1995) for commercial issues,
- **Logistics Engineering and Management** (Blanchard 1992) for Department of Defense issues,
- **Systems Engineering and Analysis** (Blanchard 1990) for management and design, issues, and
- **Life-Cycle Cost and Economic Analysis** (Fabrycky 1991) for conceptual and theoretical issues concerning LCC.

Technical societies such as the Society of Automotive Engineers include life-cycle costs in the **RMS Guidebook** (SAE 1995) with a convenient summary of the principles. Also, the Institute of Industrial Engineers includes a short section on life cycles and how they relate to life-cycle costs in the **Handbook of Industrial Engineering** (IEE 1992). LCC has been the subject of a tutorial at the annual **Reliability and Maintainability Symposium** (Blanchard 1991) which is sponsored by major technical societies.

LCC concepts are resurging. LCC limitations are accepted as normal restrictions on every engineering tool. Usefulness has been demonstrated by passing the test of time with practitioners who have learned how to minimize LCC limitations. As with all cost techniques (and typical of all engineering tools) the limitations can result in substantial setbacks when judgment is not used. Here are some of the most often cited LCC limitations:

- LCC is not an exact science, everyone gets different answers and the answers are neither wrong nor right—only reasonable or unreasonable. LCC experts do not exist because the subjects are too broad and too deep.
- LCC outputs are only estimates and can never be more accurate that the inputs and the intervals used for the estimates—this is particularly true for cost-risk analysis.

- LCC estimates lack accuracy. Errors in accuracy are difficult to measure as the variances obtained by statistical methods are often large.

- LCC models operate with limited cost databases and the cost of acquiring data in the operating and support areas is both difficult to obtain and expensive to acquire.

- LCC cost models must be calibrated to be highly useful.

- LCC models require volumes of data and often only a few handfuls of data exist—and most of the available data is suspect.

- LCC requires a scenario for: how the money expenditure model will be constructed for acquisition of equipment, how the model will age with use, how damage will occur, how learning curves for repairs and replacements will occur, how cost processors will function (design costs, labor costs, material costs, parts consumption, spare parts costs, shipping costs, scheduled and unscheduled maintenance costs) for each time period, how many years the model will survive, how many units will be produced/sold, and similar details required for building cost scenarios—most details require extensive extrapolations and obtaining facts is difficult.

- LCC models (by sellers) and cost-of-ownership (COO) models (by end-users) have credibility gaps caused by using different values in each model. Often credibility issues center on which is right and which is wrong (a win-lose issue) rather than harmonizing both models (for a win-win effort) using available data.

- LCC results are not good budgeting tools. They're effective only as comparison/trade-off tools and producing good LCC results requires a project team approach because specialized expertise is needed.

- LCC should be an integral part of the design and support process to design for the lowest long term cost of ownership. End users can use LCC for affordability studies, source selection studies of competing systems, warranty pricing and cost effectiveness studies. Suppliers find

LCC useful for identifying costs drivers and ranking the comparison of competing designs and support approaches.

- LCC, unfortunately, is only useful for Department of Defense (DoD) projects and is seldom applied to commercial areas because few practitioners exist for preparing LCC.

Remember this adage when considering LCC limitations: In the land of the blind, a one-eyed man is king! LCC can help improve our blinded sight—we don't need the most wonderful sight in the world, it just needs to be more acute than our fiercest competitor so that we have an improvement in the cost of operating our plants. DOD tools and techniques are frequently used effectively in commercial areas and this is true of life-cycle costing and numerous references to LCC papers are listed in cumulative indexes for a major symposium (1996 RAMS). Major references for LCC in the DOD area are MIL-HDBK-259 for LCC details, MIL-HDBK-276-1 and MIL-HDBK-276-2 as form guides for details and for importing data into specific software.

WHY USE LCC?

LCC helps change provincial perspectives for business issues with emphasis on enhancing economic competitiveness by working for the lowest long term cost of ownership. Too often parochial views result in ineffective actions best characterized by short term cost advantages (but long term costly decisions). Consider these typical events observed in most companies:

- **Engineering** avoids specifying cost effective, redundant equipment needed to accommodate expected costly failures so as to meet capital budgets,
- **Purchasing** buys lower grade equipment to get favorable purchase price variances,
- **Project engineering** builds plants with a 6 month view of successfully running the plant only during start-ups rather than the long term view of low cost operation,
- **Process engineering** requires operating equipment in race car driver fashion using a philosophy that all equipment is capable of operating at 150% of its rated condition without failure and they have other departments to clean-up equipment abuse,
- **Maintenance** defers required corrective/preventive actions to reduce budgets, and thus long term costs increase because of neglect for meeting short term management gains.

- **Reliability engineering** is assigned improvement tasks with no budgets for accomplishing the goals.

Management is responsible for harmonizing these potential conflicts under the banner of operating for the lowest long term cost of ownership. The glue binding these conflicts together is a teamwork approach for minimizing LCC. When properly used with good engineering judgment, LCC provides a rich set of information for making cost effective, long term decisions. LCC can be used as a management decision tool for:

- **Costing discipline-**it is concerned with operating and support cost estimates.
- **Procurement technique-**it is used as a tool to determine cost per usage.
- **Acquisition tool-**it is concerned with balancing acquisition and ownership costs.
- **Design trade-off-**it integrates effects of availability, reliability, maintainability, capability, and system effectiveness into x-y charts that are understandable for cost effective screening methods.

So why should engineers be concerned about cost details for LCC? Some facts of life that are important to help engineers <u>think like MBAs</u> and <u>act like engineers</u> for profit making enterprises:

- There are no free lunches—the customer who buys from your company pays for everything and he wants value for quality products and services at low prices.
- Companies must usually meet prices set by their marketplace competitors. Thus lower prices come from shareholder pockets. Remember, the stockholder through the board of directors is the boss, and stockholders want wealth created over time (not breaking even and not loosing money). They see time as money and money as time.
- Lenders who provide cash for new investments do not pay for anything and get fees off the top thus creating burdens for everyone. The money which a company has in its coffers is “rented” from lenders, and owners (bond holders, or stock holders). No company has enough cash to cover all the issues of the stakeholders.

- Lenders have lower risk, bond holders have medium risk, and stock holders have the highest risk for their money (they all want money from the company for the risk they take as profits go up and down with time). Engineers, as stewards for the company, must make wise decisions in the selection of processes and equipment to cover the risks incurred and thus generate wealth for the stakeholders.

- Financial performance measures are as numerous as engineering measures. What really counts for owners is return on capital employed and economic profit derived from the enterprise satisfies both debt holders and stockholders. If too much is spent for capital, achieving appropriate returns on the capital is more challenging and likewise economic profit is too low for generating adequate cash returns.

- Creating wealth for stock holders usually requires thinking about the cost of money used for projects along with promises made about repayment including interest charged on the borrowed money. Interest rates are set by market forces involving supply of money by investors, loan demand by borrowers, and inflation/deflation rates. Interest rates are always changing but two principles always remain: 1) interest received by the lender is a profit, and 2) interest paid by the borrower is always a cost.

- Borrowing money involves a risk by the lender. It costs money to borrow money. Lenders have alternatives for investing money—including not making a loan. Borrowers make promises concerning repayment of borrowed funds and the promises are worth less every year into the future because of unknowns. Thus future flow of funds are worth less every year into the unknown future by factors known as the present value (PV) whose factors are determined by a set percentage rate known as a discount rate, and the discount rate must be equal to or above the minimum attractive rate.

- Every business has a minimum rate of return for projects which should be substantially higher than borrowing rates for money. If the minimum attractive rate of return is set too high then many reasonably good projects get disqualified. If the minimum rate of return is set too low, then too many marginal projects get accepted and the business becomes a “bank”. All projects get screened against a minimum rate which also changes with time and conditions. For example, if the cost of money to a corporation is 9% then the minimum attractive rate of return may be at least 12% to merit consideration for a successful project. It's unwise to champion projects with rates of return less than the minimum attractive rate, and sometimes the best project may involve the alternative of doing nothing rather than buying into a poorly performing project. The object of successful projects is to find opportunities that are worth much more than they cost over time. Projects must exceed the minimum attractive rates of return so wealth is created for the stockholders.

- Economic calculations are well defined but the most difficult financial question is what discount rate should be used. Accounting and finance organizations set internal discount rates to make economic decisions easy for engineers (remember—the discount rate is always changing). Discount factors reflect a host of relationships and considerations which include very low risk investment returns such as US Government T-bills, factors for projects such as estimated uncertainty errors, internal rates of returns, and so forth. Discount factors vary by company and by time. In general, consider a typical discount value of 12% which is neither very low or very high for calculations which will follow. Using the discount rate of 12%, consider the results for two questions using $FV = PV*(1+i)^n$ where FV is future value, PV is present value, i, is discount rate, and n is number of years into the future:
    1) What is the present value (PV) of US$1.00 today over time?
    2) What is the future value (FV) of US$1.00 received over time?

  Cash flows into and out of a business according to cash outlays and receipts of business transactions. The discounting method is used to summarize transactions over the life of the investment in terms of present or future dollars. Discount rates in Table 1 are used as multipliers or dividers to put financial transactions into the present value of money to answer the two questions posed above.

Table 1: Present Value and Future Value

Discount Rate = 12%																					
Years hence	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Present value of US$1.00	1.00	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29	0.26	0.23	0.20	0.18	0.16	0.15	0.13	0.12	0.10
Future value of US$1.00	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11	3.48	3.90	4.36	4.89	5.47	6.13	6.87	7.69	8.61	9.65

- Net present value (NPV) is an important economic measure for projects or equipment taking into account discount factors and cash flow. The present value (PV) of an investment is the maximum amount a firm could pay for the opportunity of making the investment without being financially handicapped. The net present value (NPV) is the present value of proceeds minus present value of outlays. Net present value calculations start with a discount rate, followed by finding the present value of the cash proceeds expected from the investment, then followed by finding the present value of the outlays: the net of this calculation is the net present value. Clearly high NPV projects and processes provide wealth for the stockholders. Cash availability and strategies aside, when competing projects are judged for acceptance, the project with the greatest NPV is usually the winner.

- Cash flow for any company is very important. Positive cash flow into the company assures a going concern. The concept is simple: no cash, no company! One project can't borrow cash from another project so all cash generating actions are usually judged by themselves. The term cash flow is generalized and refers to the flow of money. Cash flow is not identical with the accounting terms of profits or income. For projects, the general view is that cash flows out in one or more years and cash begins to flow in for a series of many years. The amount of cash "thrown off" by a project is an important consideration and a helpful criteria for evaluating projects. For many projects cash flow results from cost savings, depreciation, and taxes. Of course depreciation schedules change as accounting departments select the schedule that legally results in the greatest profits and tax rates change from political considerations. Most accounting departments use the same general form for calculating relative changes in cash flow although specific details are highly variable—for example, the straight line depreciation schedule may be used for accounting profit purposes and accelerated depreciation for tax purposes. Depreciation is a non-cash cost and must be excluded or added back to determine actual cash flow. Cash flows (after taxes to get the real flow of cash) in each period are adjusted by a discount factor to calculate present value for each year. The net present value is the sum of all present values for the allowed time periods.

- Most fixed assets and other projects have a limited useful life. Accounting practices gradually change fixed assets into expense with a process called depreciation over the accepted long life of an asset. All equipment has a finite life based on both deterioration and obsolescence. Judgment is required in estimating and setting actual service life of assets. Thus, life may be different from the depreciation guidelines (note the emphasis on guidelines) published by the USA Internal Revenue Service in publication number 456. Two common methods are used for calculating depreciation based on acquisition cost less salvage:

1) Straight line method is based on consumption of a fixed percentage of the equipment cost. Often straight line depreciation is used for internal accounting reports of profit/loss. 2) Accelerated method is based on the amount of service provided where a larger amount of depreciation is consumed in the early years and the depreciation for each year is found by applying a rate to the book value of the asset at the beginning of that year rather than to the original cost of the asset—book value is cost less total depreciation accumulated up to that time. Accelerated depreciation is often used for tax and cash reporting purposes. Depreciation methods are different for accounting and tax considerations. Remember that depreciation is non-cash and is only a process of allocation to future periods. For the calculations below, the straight line depreciation schedule will be used and Table 2 shows the contrast between straight line and double declining-balance.

Table 2: Straight Line and Double Declining Depreciation

Depreciation Schedule For A US$1 Investment																						Depreciation Total
Years hence	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Straight line	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.00
Double declining	0.00	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.88

- Income tax rates vary and may require inclusion of state as well as federal taxes. For calculation purposes, consider the tax rate is 38% based on the profit before tax numbers. Profit before taxes may be positive or negative. When profit before tax is negative, the company receives a tax credit either a carry-back or carry-forward. When profit before tax is positive, the company pays taxes. For a project or process, tax numbers are used to calculate cash flows. After the tax is included, the cash flow is discounted to get present value, and the sum of all present values gives the NPV.

- When you know net present values for the project life, then the discounted cash flow (DCF) rate can be calculated to arrive at a profitability index. The discounted cash flow rate is the return which forces the NPV to zero. It’s the maximum cost of capital that can be paid just to break even on the project. The DCF index defines an economical quality value for the project and is useful for comparing projects of different sizes. Large DCFs are desirable but small investments and big savings make the number unbelievable. The DCF index sometimes has problems in ranking project desirability so base final decisions on the NPV—of course this assumes a common time period for the life of the items.

- If equipment life among alternatives is not the same, then a more complicated analysis is required to divide the NPV by an annuity factor. The annuity factor depends on equipment lifetime, discount rates, and equivalent annual cash flow to correct for unequal equipment life. This calculation puts NPV alternatives on an equivalent annual basis using an annuity factor (AF) where AF = $[((1+i)^N - 1)/i*(1+i)^N]$ and i = discount rate, N = equipment life (refer to the uniform-series present-worth, USPW, calculation in Hicks 1985). The annual equivalent NPV, (AENPV) is found by AENPV = NPV/AF. For example if two competing projects each project a NPV = \$150,000 using a DCF = 12% and case 1 has equipment life of 5 years while case 2 has a life of 10 years. By common sense, case 1 is preferable, but here is how it works out: $AF_{N=5}$ = 3.605 and $AF_{N=10}$ = 5.650 so that $AENPV_{N=5}$ = \$41,611 and $AENPV_{N=10}$ = \$26,547. This shows the five year life case is 1.6 fold more attractive.

Engineers must be concerned with life cycle costs for making important economic decisions through engineering actions. Management deplores engineers who are engineering smart but economics stupid. Engineers must get the equation balanced to create wealth for stockholders. Often this means: **stop** doing some things the old way, and **start** doing new things in smarter ways.

Example 1 shown below illustrate the above ideas and concepts for a financial analysis. This example is **not** a LCC model but it is typical of how equipment is justified:

Example 1: Two alternatives are being considered for installing an on-line spare pump in parallel with an existing ANSI grade pump to avoid outages that have plagued a chemical plant. The parallel pump (which will be operated every other week on a rotation schedule and when ever pump failure occurs—this is an incremental investment/operation) will save, on the average, US\$12,000 per year in out-of-pocket production losses for product which cannot be shipped during the outages. Pumps under consideration, with expected 20 year lives, are: 1) another ANSI pump at US\$8,000 installed cost, 2) an ANSI enhanced pump at US\$18,000 installed cost, and 3) do nothing. Which course of action should we recommend using the concepts described above? Consider alternatives given below—by the way, year 0 is now, and year 1 is next year.

Table 4: Financial NPV Without LCC Content

	Year																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Alternative #1-ANSI Pump																					
Capital Cost	8000																				
Savings		12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000
Depreciation		400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Profit b/4 taxes		11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600	11600
Tax Provision		-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408	-4408
Net Income		7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192	7192
Add Back Depreciation		400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Cash Flow	-8000	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592	7592
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11	3.48	3.90	4.36	4.89	5.47	6.13	6.87	7.69	8.61	9.65
Present Value	-8000	6779	6052	5404	4825	4308	3846	3434	3066	2738	2444	2183	1949	1740	1553	1387	1238	1106	987	881	787
Net Present Value	**$ 48,708**	using a 12% discount rate																			
Alternative #2-ANSI Enhanced Pump																					
Capital Cost	18000																				
Savings		12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000
Depreciation		900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Profit b/4 taxes		11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100	11100
Tax Provision		-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218	-4218
Net Income		6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882	6882
Add Back Depreciation		900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Cash Flow	-18000	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782	7782
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11	3.48	3.90	4.36	4.89	5.47	6.13	6.87	7.69	8.61	9.65
Present Value	-18000	6948	6204	5539	4946	4416	3943	3520	3143	2806	2506	2237	1997	1783	1592	1422	1269	1133	1012	904	807
Net Present Value	**$ 40,127**	using a 12% discount rate																			
Alternative #3-Do Nothing																					
Capital Cost	0																				
Savings		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Depreciation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Profit b/4 taxes		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tax Provision		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Net Income		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Add Back Depreciation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cash Flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11	3.48	3.90	4.36	4.89	5.47	6.13	6.87	7.69	8.61	9.65
Present Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Net Present Value	**$ -**	using a 12% discount rate																			

By this financial analysis, installing an ANSI pump results in the **largest** NPV.

These spread sheets are the usual justifications prepared by accounting departments, however, this analysis **does not** take into account life cycle costs. Accounting departments will use this technique unless engineers provide details about how equipment survives or dies in operating environments. Adding expected failure rates and renewals makes the accounting analysis smarter and gets the analysis closer to real world conditions.

Should the ANSI pump be installed based on the favorable NPV? That depends upon the company's demand for cash and other details to be described below.

WHAT GOES INTO LIFE CYCLE COSTS?

LCC includes every cost that is appropriate and appropriateness changes with each specific case which is tailored to fit the situation. LCC follows a process (Fabryck 1991—Appendix A):

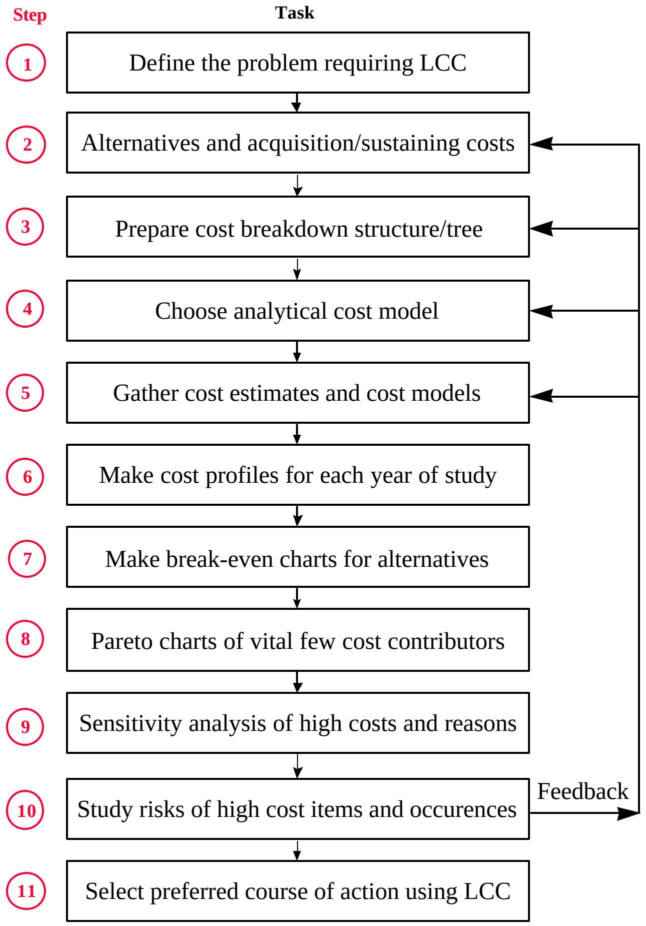


Figure 1: Life Cycle Costing Process

The basic tree for LCC starts with a very simple tree based on the costs for acquisition and the costs for sustaining the acquisition during its life as shown in Figure 2.

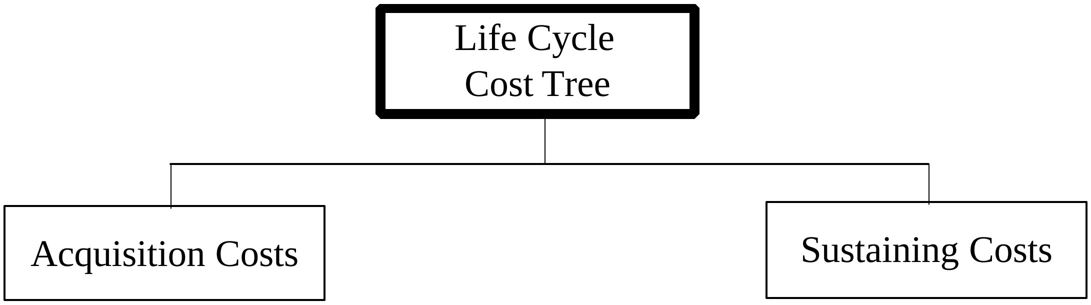


Figure 2: Top Levels Of LCC Tree

Acquisition and sustaining costs are not mutually exclusive. If you acquire equipment or processes, they always require extra costs to sustain the acquisition, and you can't sustain without someone having acquired the item. Acquisition and sustaining costs are found by gathering the correct inputs, building the input database, evaluating the LCC and conducting sensitivity analysis to identify cost drivers.

Frequently the cost of sustaining equipment is 2 to 20 times the acquisition cost. Consider the cost for a simple ANSI pump—the power cost for driving the pump during it's life time is many times larger than the acquisition cost of the pump. Are ANSI pumps bought with an emphasis on energy efficient drivers and energy efficient rotating parts—or is the acquisition simply based on the cheapest purchase price?

The often cited rule of thumb is 65% of the total LCC is set when the equipment is specified!! This means do not consider the specification process lightly. Realize the first obvious cost (hardware acquisition) is usually the smallest amount of cash that will be spent during the life of the acquisition and most sustaining expenses are not obvious. Every example has its own unique set of costs and problems to solve for minimizing LCC. Minimizing LCC pushes-up NPV and creates wealth for stockholders. Finding LCC requires finding details for both acquisition and sustaining costs with many details involved in the effort.

Acquisition costs have several branches for the tree as shown in Figure 3.

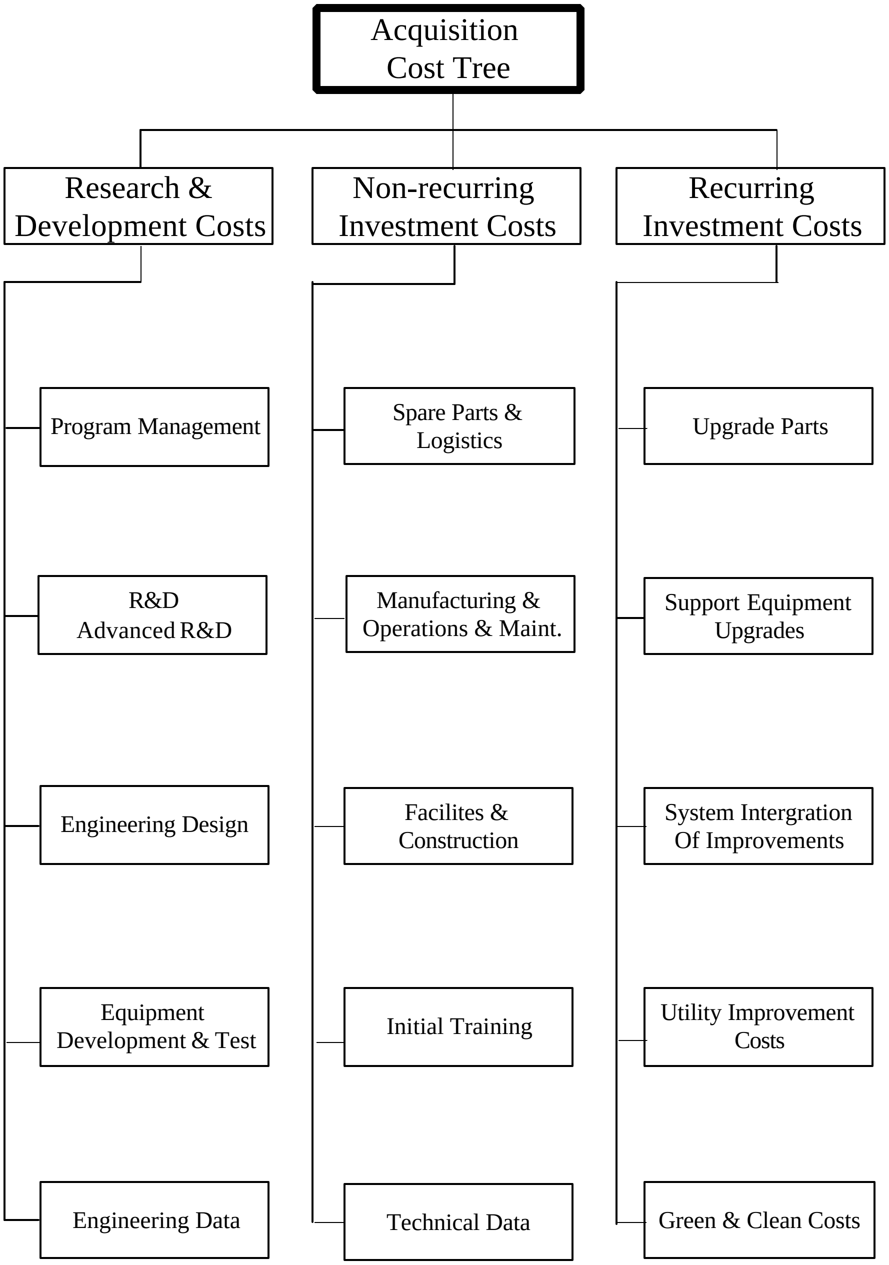


Figure 3: Acquisition Cost Tree

Each branch of the acquisition tree also has other branches which are described in detail in other references (SAE 1993) and (Fabrycky 1991).

Sustaining costs have several branches for the tree as shown in Figure 4.

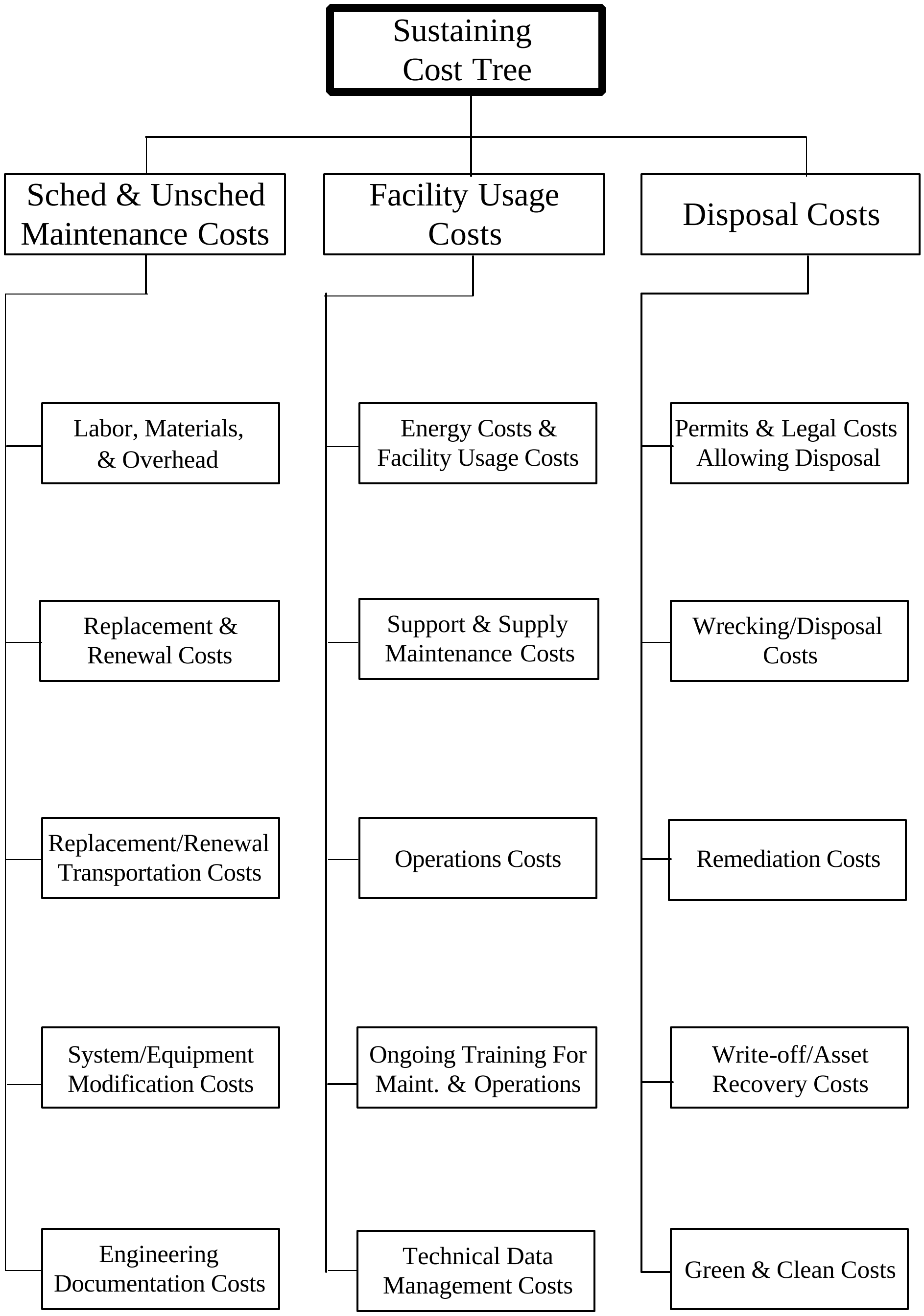


Figure 4: Sustaining Cost Tree

What cost goes into each branch of the acquisition and sustaining branches? It all depends on the specific case and is generally driven by common sense. Consider the details under each category which is shown below. Of course, building a nuclear power plant to generate electricity requires special categories under each item of acquisition cost and sustaining cost. Building a pulp and paper mill or modifying coker drums at a refinery to prevent characteristic over-stress which occurs during quench cycles would have different cost structures than for building a nuclear reactor. Include the appropriate cost elements and discard the elements which do not substantially influence LCC. Consider these alternative LCC models as described by (Raheja 1991):

1) LCC = non-recurring costs + recurring costs,

2) LCC = initial price + warranty costs + repair, maintenance, and operating costs to end users;

3) LCC = manufacturer's cost + maintenance costs and downtime costs to end users.

SAE (SAE 1993) also has a LCC model directed toward a manufacturing environment:

4) LCC = acquisition costs + operating costs + scheduled maintenance + unscheduled maintenance + conversion/decommission.

The SAE model breaks down the costs as shown in Figure 5.

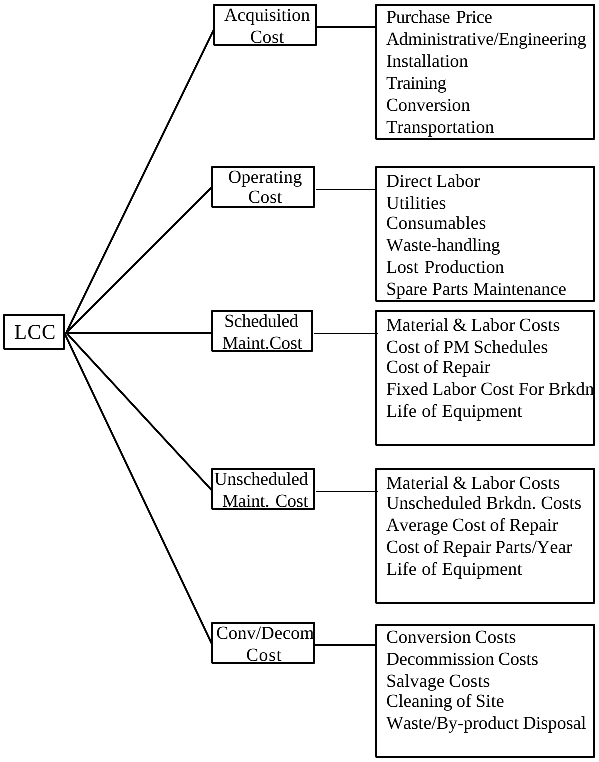


Figure 5: SAE Model of LCC

The LCC models above, and much more complicated models described in the British Standards BS-5760 (BSI 1983), include costs to suppliers, end users, and "innocent bystanders"—in short, the costs are viewed from a total systems perspective. LCC vary with events, time, and conditions. Many cost variables are not deterministic but are truly probabilistic. This usually requires starting with arithmetic values for cost and then growing the cost numbers into the more accurate, but more complicated, probabilistic values.

TRADE-OFF TOOLS FOR LCC

One helpful tool for easing LCC calculations involving probabilities is the effectiveness equation which gives a figure-of-merit for judging the chances of producing the intended results. The effectiveness equation is described in several different formats (Blanchard 1995, Kececioglu 1995, Landers 1996, Pecht 1995, Raheja 1991) where each element varies as a probability and the issue is finding a system effectiveness value which gives lowest long term cost of ownership:

System effectiveness = Effectiveness/LCC

Cost is a measure of resource usage (cost estimates can never include all possible elements but hopefully includes the most important elements). Effectiveness is a measure of value received (effectiveness rarely includes all value elements as many are too difficult to quantify) and effectiveness varies from 0 to 1:

Effectiveness = availability * reliability * maintainability * capability
= availability * reliability * performance (maintainability * capability)
= availability * dependability (reliability * maintainability) * capability.

In plain English, the effectiveness equation is the product of: the chance the equipment or system will be available to perform its duty, it will operate for a given time without failure, it is repaired without excessive loss maintenance time and it can perform its intended production activity according to the standard. Each element of the effectiveness equation is premised on a firm datum which changes with name plate ratings to obtain a true value that lies between 0 and 1:

- Availability deals with the duration of up-time for operations and is a measure of *how often* the system is alive and well. It is often expressed as (up-time)/(up-time + downtime) with many different variants. Up-time and downtime refer to dichotomized conditions. Up-time refers to a capability to perform the task and downtime refers to not being able to perform the task, i.e., up-time ≡ not downtime. Also availability may be the product of many different terms such as:

$$A = A_{hardware} * A_{software} * A_{humans} * A_{interfaces} * A_{process}$$

and similar configurations. Availability issues deal with at least three main factors (Davidson 1988) for: 1) increasing time to failure, 2) decreasing downtime due to repairs or scheduled maintenance, and 3) accomplishing items 1 and 2 in a cost effective manner as availability grows, the capacity for making money increases because the equipment is in-service a larger percent of time.

Three frequently used availability terms (Ireson 1996) are explained below. **Inherent availability**, *as seen by maintenance personnel,* (excludes preventive maintenance outages, supply delays, and administrative delays) is defined as:

$$A_i = MTBF/(MTBF + MTTR)$$

Achieved availability, *as seen by the maintenance department*, (includes both corrective and preventive maintenance but does not include supply delays and administrative delays) is defined as:

$$A_a = MTBM/(MTBM + MAMT)$$

Where MTBM is mean time between corrective and preventive maintenance actions and MAMT is the mean active maintenance time.

Operational availability, *as seen by the user*, is defined as:

$$A_o = MTBM/(MTBM + MDT)$$

Where MDT is mean down time.

A few key words describing availability in quantitative words are: on-line time, stream factor time, lack of downtime, and a host of local operating terms including a minimum value for operational availability—even though the equipment many not be in actual operation, the production departments wants it available at least a specified amount of time to complete their tasks. An example of 98% availability for a continuous process says to expect up-time of 0.98*8760 = 8584.8 hr/yr and downtime of 0.02*8760 = 175.2 hrs/yr as availability + unavailability = 1. A system must be available (ready for service) and reliability (absence of failures) to produce effective results.

- Reliability deals with reducing the frequency of failures over a time interval and is a measure of *the probability for failure-free operation* during a given interval, i.e., it is a measure of success for a failure free operation. It is often expressed as

  $$R(t) = \exp(-t/MTBF) = \exp(-\lambda t)$$

  where λ is constant failure rate and MTBF is mean time between failure. MTBF measures the time between system failures and is easier to understand than a probability number. For exponentially distributed failure modes, MTBF is a basic figure-of-merit for reliability (and failure rate, λ, is the reciprocal of MTBF). For a given mission time, to achieve high reliability, a long MTBF is required. Also reliability may be the product of many different reliability terms such as

  $$R = R_{utilities} * R_{feed\text{-}plant} * R_{processing} * R_{packaging} * R_{shipping}$$

  and similar configurations.

To the user of a product, reliability is measured by a long, failure free, operation. Long periods of failure free interruptions results in increased productive capability while requiring fewer spare parts and less manpower for maintenance activities which results in lower costs. To the supplier of a product, reliability is measured by completing a failure free warranty period under specified operating conditions with few failures during the design life of the product.

Improving reliability occurs at an increased capital cost but brings with it the expectation for improving availability, decreasing downtime and smaller maintenance costs, improved secondary failure costs, and results in better chances for making money because the equipment is free from failures for longer periods of time. While general calculations of reliability pertain to constant failure rates, detailed calculations of reliability are based on consideration of the failure mode which may be infant mortality (decreasing failure rates with time), chance failure (constant failure rates with time), or wear-out (increasing failure rates with time).

A few key words describing reliability in quantitative words are: mean time to failure, mean time between failures, mean time between/before maintenance actions, mean time between/before repairs, mean life of units in counting units such as hours or cycles, failure rates, and the maximum number of failures in a specified time interval. An example of a mission time of one year with equipment which has a 30 year mean time to failure gives a reliability of 96.72% which is the probability of successfully competing the one year time interval without failure. The probability for failure is 3.278% as reliability + unreliability = 1. High reliability (few failures) and high maintainability (predictable maintenance times) tend toward highly effective systems.

- Maintainability deals with duration of maintenance outages or *how long* it takes to achieve (ease and speed) the maintenance actions compared to a datum. The datum includes maintenance (all actions necessary for retaining an item in, or restoring an item to, a specified, good condition) is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance. Maintainability characteristics are usually determined by equipment design which set maintenance procedures and determine the length of repair times.

The key figure of merit for maintainability is often the mean time to repair (MTTR) and a limit for the maximum repair time. Qualitatively it refers to the ease with which hardware or software is restored to a functioning state. Quantitatively it has probabilities and is measured based on the total down time for maintenance including all time for: diagnosis, trouble shooting, tear-down, removal/replacement, active repair time, verification testing that the repair is adequate, delays for logistic movements, and administrative maintenance delays. It is often expressed as

$$M(t) = 1 - \exp(-t/MTTR) = 1 - \exp(-\mu t)$$

where μ is constant maintenance rate and MTTR is mean time to repair. MTTR is an arithmetic average of how fast the system is repaired and is easier to visualize than the probability value. Note this simple, easy to use criteria, is frequently expressed in exponential repair times rather than the more accurate but very cumbersome log-normal distributions of repair times describing maintenance times which are skewed to the right. The maintainability issue is to achieve short repair times for keeping availability high so that downtime of productive equipment is minimized for cost control when availability is critical.

An example of a stated maintainability goal is a 90% probability that maintenance repair times will be completed in 8 hours or less with a maximum repair time of 24 hours. This requires a system MTTR of 3.48 hours. Also the cap of 24 hours (99.9% of repairs will be accomplished in this time, or less) requires control of three main items of downtime: 1) active repair time (a function of design, training, and skill of maintenance personnel), 2) logistic time (time lost for supplying the replacement parts), and 3) administrative time (a function of the operational structure of the organization). The probability for not meeting the specified 8 hour repair interval in this example is 10% based on a MTTR of 3.48 hours as maintainability + unmaintainability = 1.

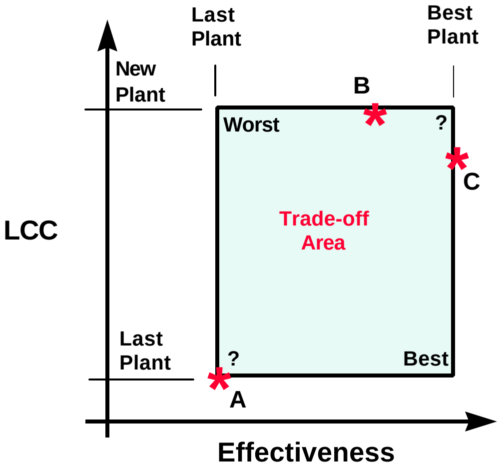
High availability (high up-time), high reliability (few failures) and high maintainability (predictable and short maintenance times) tend toward highly effective systems if capability is also maintained a high levels.

- Capability deals with productive output compared to inherent productive output which is a measure of *how well* the production activity is performed compared to the datum. This index measure the systems capability to perform the intended function on a system basis. Often the term is the synonymous with productivity which is the product of efficiency multiplied by utilization. Efficiency measures the productive work output versus the work input. Utilization is the ratio of time spent on productive efforts to the total time consumed. For example, suppose efficiency is 80% because of wasted labor/scrap generated, and utilization is 82.19% because the operation is operated 300 days per year out of 365 days. The capability is 0.8*0.8219 = 65.75%

- Dependability is the product of reliability and maintainability. It measures *how long* things perform. Related issues about non-operational influences are not included.

- The importance of quantifying elements of the effectiveness equation (and their associated costs) is to find areas for improvement to increase overall effectiveness and reduce losses. For example, if availability is 98% and capability is 65%, the opportunity for improving capability is usually much greater than for improving availability.

System effectiveness equations (Effectiveness/LCC) are helpful for understanding benchmarks, past, present, and future status as shown in Figure 6 for understanding trade-off information.



	A	B	C
Parameter	Last Plant	New Plant	Best Plant
Availability	0.95	0.95	0.98
Reliability	0.3	0.4	0.6
Maintainability	0.7	0.7	0.7
Capability	0.7	0.8	0.6
Effectiveness	0.14	0.22	0.25
LCC	80	100	95

Figure 6: Benchmark Data Shown In Trade-Off Format

The lower right hand corner of Figure 6 brings much joy and happiness often described as “bang for the buck” (Weisz 1996). The upper left hand corner brings much grief. The remaining two corners raise questions about worth and value. The system effectiveness equation is useful for trade-off studies (Brennan 1985) as shown in the attached outcomes in Figure 7.

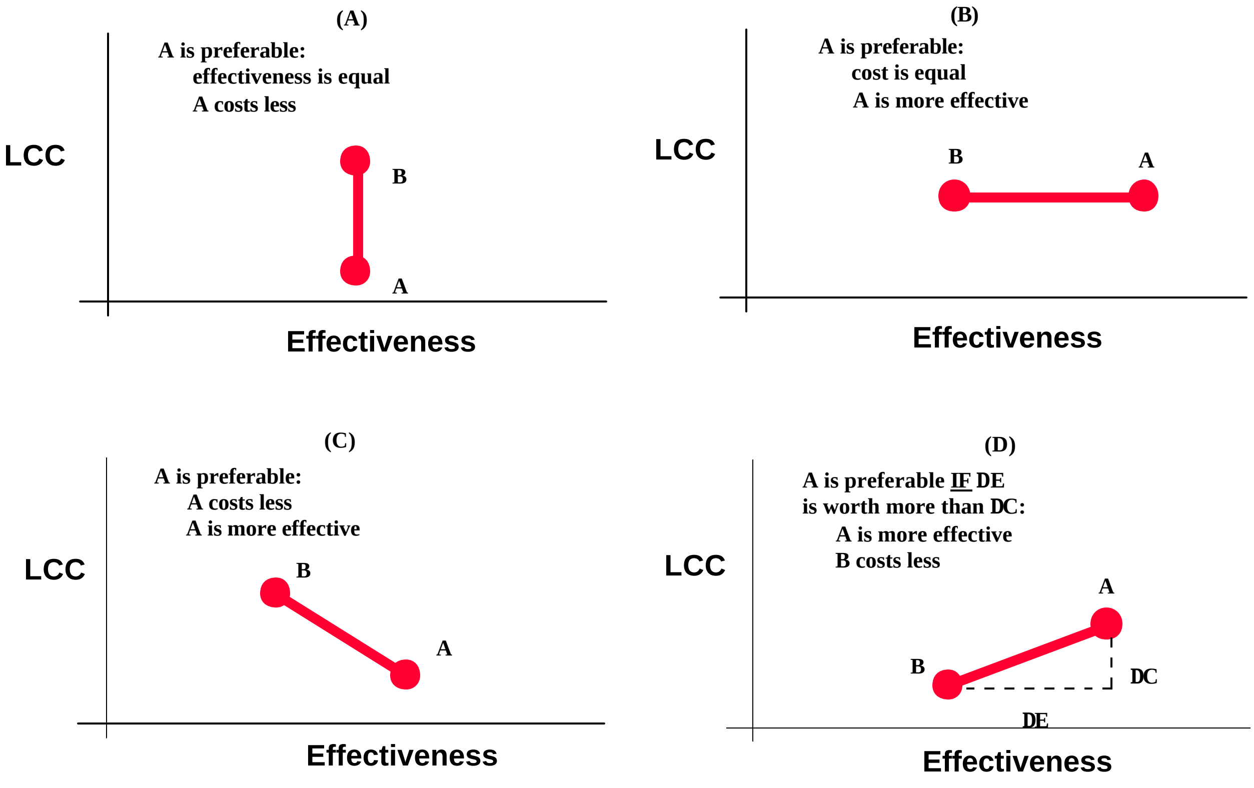


Figure 7: Some Possible Outcomes From Trade-Off Studies

System effectiveness equations have great impact on the LCC because so many decisions made in the early periods of a project carve the value of LCC into stone. About 2/3's of the total LCC are fixed during project conception (Followell 1995, Yates 1995) even though expenditure of funds will flow at a later time (Brennan 1985), and the chance to influence LCC cost reductions (Blanchard 1991) grows smaller as shown in Figure 8.

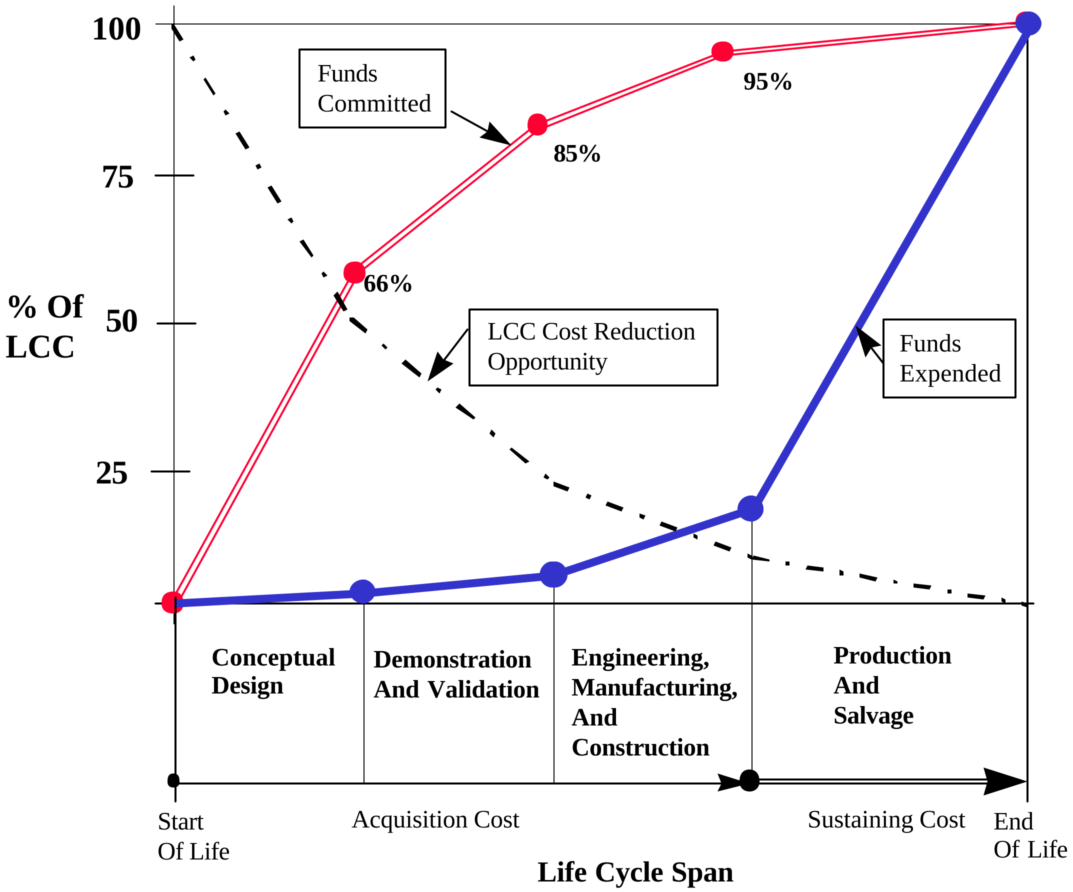


Figure 8: Funding Trends By Commitment And Expenditure

Engineering sizes and aims the cost funnel, and production/maintenance pours money into the funnel. Consider LCC early in the game where the final outcome can be influenced for better business results. Making major changes in LCC when the project is turned over to production is not possible because the die has been cast. Breaking poverty cycles of building cheap plants and repairing them often--at great expense--can be accomplished in at least two ways: 1) use LCC techniques, or 2) make the capital project team indentured servants for at least 8 years to operate the plant so that new projects are designed for the least long term costs of ownership so it builds wealth for stockholders. Either method is effective at producing wealth because thoughtful, value judgments are used rather than minimizing first cost only to get high long term cost of ownership—however it requires producing some facts for getting the action started for improvements!

ENGINEERING FACTS

LCC requires facts which are driven by data. Most engineers are of the opinion they lack data. In fact, data is widely available as a starting point for LCC (Bloch 1995). Often data resides in local computer files but it has not been analyzed or put to effective use. Analysis can start with arithmetic analysis and grow to more complicated statistical analysis (Barringer 1995). Follow the guidelines for each step listed in Figure 1 to work-out a typical engineering problem (remember, a single right or wrong method/solution does not exist--many methods and routes can be used to find LCC). If you disagree with the cost or life data, substitute your own values determined by local operating conditions, local costs, and local grades of equipment.

Step 1: Define the problem. A pump is operating without an online spare. At pump failure, the process shuts down and financial losses are incurred as each hour of down time results in a gross margin loss of US$4,000/hour of outage. Find an effective LCC alternative as the plant has an estimated 10 years of remaining life and is expected to be sold-out during this interval.

Step 2: Alternatives and acquisitions/sustaining costs. Consider three obvious alternatives for LCC (other alternatives exist for solving this problem, however, the list is pared for brevity):

1. Do nothing. Continue solo ANSI pump operations with a 100 horsepower, 1750 RPM, 250 psi, 500 gpm, 70% hydraulic efficiency, while pumping fluid with a specific gravity of 1.

2. Add a new, second ANSI pump in parallel (literally in redundant standby) which can be started immediately without the loss of production upon failure of the running pump. Alternate running of the parallel unit every other week to avoid typical failures incurred by non-operating equipment. The capital costs for the second pump is $8,000 plus $3,000 for check/isolation valves, plus $2,500 for installation.

3. Remove the existing solo ANSI pump and replace it with a new solo API pump with the same performance as for the ANSI model. The API pump cost $18,000 plus $3,500 for installation and the installation will incur a four hour loss of production for connecting the new pump.

Step 3: Prepare cost breakdown structure/tree.

For the do nothing case, the cost breakdown structure will incur cost is these categories:

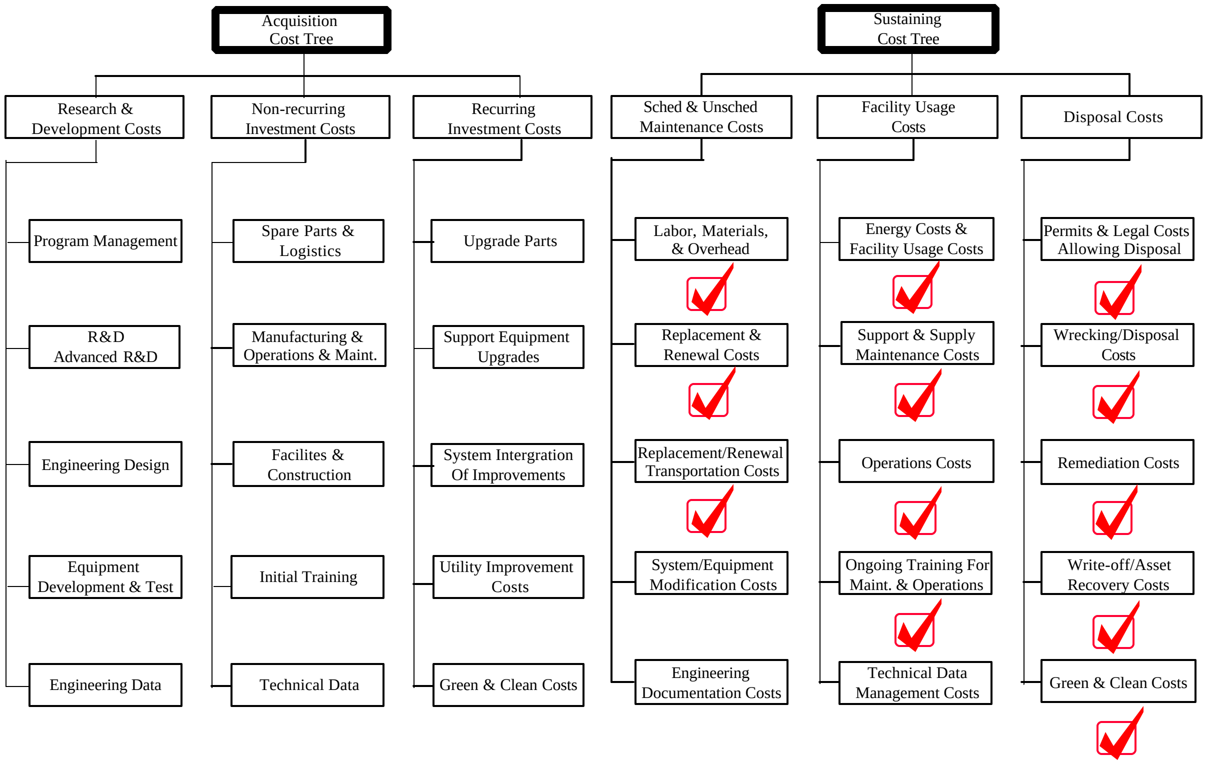


Figure 9: Cost Components For Solo ANSI Pump

For the redundant ANSI case, the cost breakdown structure will incur cost is these categories:

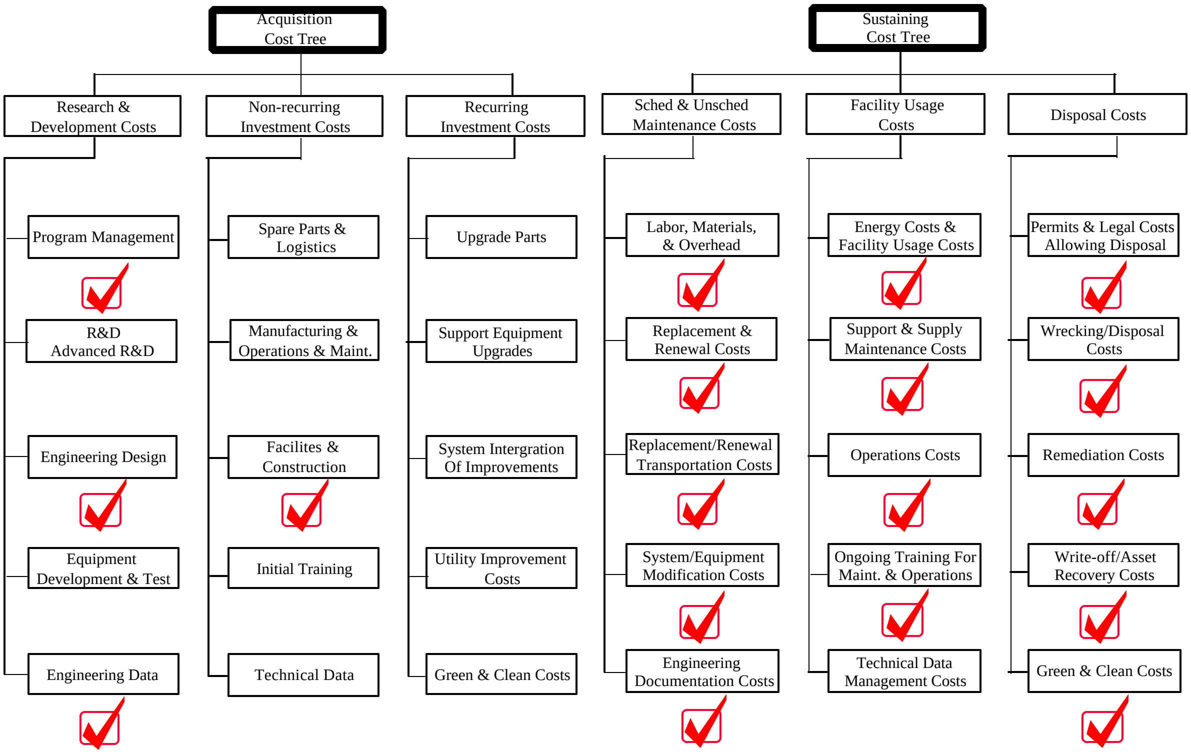


Figure 10: Cost Components For Parallel/Redundant ANSI Pumps

For the API pump case, the cost breakdown structure will incur cost is these categories:

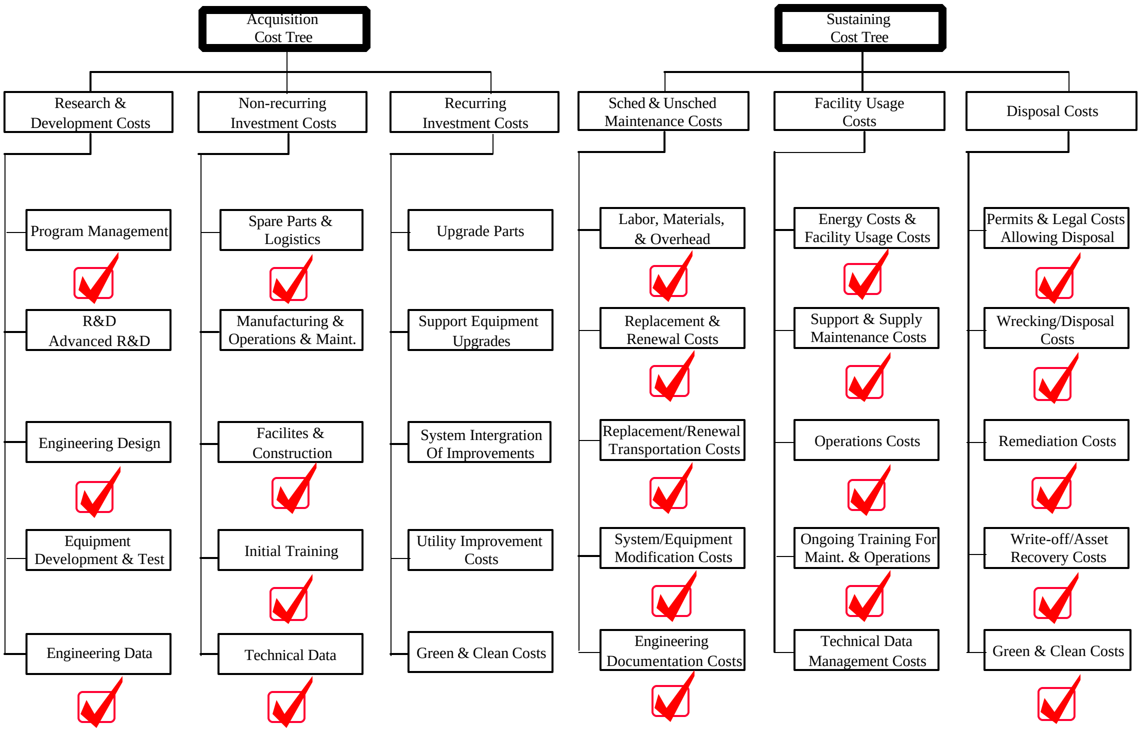


Figure 11: Cost Components For Solo API Pump

The individual details for each case will become obvious in step 5

Step 4: Choose analytical cost model.

The model used for this case is explained in an engineering spreadsheet. The spreadsheet merges cost details and failure details to prepare the NPV calculations. Failure costs are prorated into each year since the specific time for failure, because of chance events, is not known.

The same spreadsheet will be used with more details when statistical uncertainty is added in a section which follows.

Step 5: Gather cost estimates and cost models.

This is the complicated section where all the details are assembled. Of course the more thorough the collection process, the better the LCC model. For this tutorial, the details have been shortened with enough just information described to show the trends.

Alternative #1-Do nothing case--the datum: Use the following details from plant experience—

Assume all of the equipment follows the exponential distribution for reliability with constant failure rates. Note the reciprocal of failure rate is the mean time to failure. Since failure rates are constant, use one year time buckets to collect the cost of failures per year as the literal failure date is unknown. Use the following assumptions based on an accounting principle that costs will follow activity—in this case it will follow failure activity.

Capital cost are zero as the solo ANSI pump is currently a sunk cost and will not change.

Lost gross margin occurs at US$4000/hour when the process is down for repairs.

Annual power cost for running the pump is US$165/yr per horsepower. The plant incurs 1.6 power outages each year for an average downtime of 0.5 hours, and this cost is charged into plant overhead rather than to individual pieces of equipment.

Annual power costs are: (US$165/hp-yr)*(100 hp) = US$16500.

Pump seals have a mean time to failure of 3 years. When seal failure occurs, 8 hours of downtime is also lost production time. Maintenance crew costs for labor, incidental materials, and expense are US$100/hr. Seal replacement costs are US$1500/seal plus US$300/incident for bearing replacements which occur as good maintenance practice while the pump is disassembled. Seal and bearing transportation costs are usually expedited and cost US$150 per incident.

Annual seal costs are: (1 yr/3 yrs/failure)*{US$(1500+300+150) + (US$100/hr)*8 hrs
+ (US$4000/hr* 8hrs)} = US$11583

Pump shafts have a mean time to failure of 18 years. When shaft failure occurs, 10 hours of downtime is also lost production time. Maintenance crew costs for labor, incidental materials, and expense are US$100/hr. Shaft replacement costs are US$2500/shaft plus US$1800/incident for seal and bearing replacements which occur as good maintenance practice while the pump is disassembled. Shaft, seal, and bearing transportation costs are usually expedited and cost US$450 per incident.

Annual shaft costs are: (1 yr/18 yrs/fail.)* {US$(2500+1800+450) + (US$100/hr)*10 hrs
+ (US$4000/hr* 10hrs)} = US$2542

Pump impellers have a mean time to failure of 12 years. When impeller failure occurs, 8 hours of downtime is also lost production time. Maintenance crew costs are US$100/hr. Impeller replacement costs are US$3000/impeller plus US$1800/incident for seal and bearing replacements which occur as good maintenance practice while the pump is disassembled. Impeller, seal, and bearing transportation costs are expedited and cost US$750 per incident.

Annual impeller costs are: (1 yr/12 yrs/failure)*{US$(3000+1800+750)
+ (US$100/hr)*8 hrs + (US$4000/hr*8hrs)} = US$3171

Pump housings (scroll end) have a mean time to failure of 18 years. When housing failures occur, 14 hours of downtime is also lost production time. Maintenance crew costs are US$100/hr. Housing replacement costs are US$3000/housing plus US$1800/incident for seal and bearing which occur as good maintenance practice while the pump is disassembled. Housing, seal, and bearing transportation costs are expedited and cost US$1150 per incident.

Annual housing costs are: (1 yr/18 yrs/failure)*{US$(3000+1800+1150)
+ (US$100/hr)*14 hrs + (US$4000/hr*14hrs)} = US$3519

Pump bearing sets (a set = 2 bearings) have a mean time to failure of 4 years. When bearing failure occurs, 8 hours of downtime is also lost production time. Maintenance crew costs are US$100/hr. Bearing replacement costs are US$300/bearing plus US$1500/incident for seal replacement which occurs as good maintenance practice while the pump is disassembled. Bearing and seal transportation costs are usually expedited and cost US$300 per incident.

Annual bearing costs are: (1 yr/4 yrs/failure)*{US$(300+1500+300)
+ (US$100/hr)*8 hrs + (US$4000/hr*8hrs)} = US$8688

Motors have a mean time to failure of 12 years considering all causes. (Motors have many parts and can fail from many reasons. A thorough analysis would be more accurate than this overview approach taken by lumping all details into one MTBF number.) When motor failure occurs, 8 hours of downtime is also lost production time as the motor is swapped for a similar unit in stores. Maintenance crew costs are US$100/hr. Motor replacement costs are US$3000/motor. Motor transportation costs for expedited delivery are US$500.

Annual motor costs are: (1 yr/12 yrs/failure)*{US$(3000+500)
+ (US$100/hr)*8 hrs + (US$4000/hr*8hrs)} = US$3025

Couplings have a mean time to failure of 8 years considering all causes. When coupling failure occurs, 8 hours of downtime is also lost production time. Maintenance crew costs for labor, incidental materials, and expense are US$100/hr. Coupling replacement costs are US$400. Coupling transportation costs for expedited delivery are US$300.

Annual coupling costs are: (1 yr/8 yrs/failure)*{US$(400+300)
+ (US$100/hr)*8 hrs + (US$4000/hr*8hrs)} = US$4188

Maintenance visits the pump monthly for routine PM inspection, lube oil addition/change out, and emissions tests. Maintenance cost is US$50/hour for labor, incidental materials, and expense with 1 hour on the average charged per visit. No failure times are incurred during this activity.

Annual maintenance PM costs are: (12 visits*1hr/visit)*US$50/hr = US$600

Operations visits the pump once per week for routine PM inspection and vibration logging. Operations cost is US$35/hour for labor and expense, with 0.2 hours charged for each visit.

Annual operations PM costs are: (52 visits*0.2hr/visit)*US$35/hr = US$364

The Vibration Department receives vibration data from operations by e-mail and scans the data weekly for abnormalities. Surveillance cost is US$50/hour for labor and expense, and on the average, 0.2 hours is charged for each weekly visit.

Annual Vibrations PM costs are: (52 visits*0.2hr/visit)*US$50/hr = US$520

Maintenance and operations conduct a joint tail-gate training session on good maintenance and operation practices for this pump once per year. Three people from Maintenance attend at US$50/hr-person and three people from Operations attend at US$35/hr-person—the training session consumes and elapsed time of 0.5 hours.

Annual training costs are: (0.5 hr*(3people*US$50+3people*US$35)) = US$128

Disposal costs will occur as a lump at the end of the ten year remaining life are expected to be: US$500 for permits and legal costs associated with disposition, US$500 for wrecking/disposal costs, US$1000 for remediation costs, US$0 for write-off/recovery costs, and US$1000 estimated green/clean costs associated with disposal of the asset. These costs will occur in the final year. Table 4 shows non-annualized acquisition and sustaining costs for the existing solo ANSI pump.

Table 4: Non-annualized Acquisition And Sustaining Costs For Solo ANSI Pump

ANSI Pump:

Cost Element	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition Costs:											
Program Management	0										
Engineering Design	0										
Engineering Data	0										
Spare parts & Logistics	0										
Facilities & Construction	0										
Initial Training	0										
Technical Data	0										
Capital Equipment	0										
Sustaining Costs:											
Documentation Costs		0									
Disposal Costs											3000
Total =	0	0	0	0	0	0	0	0	0	0	3000

Table 5 shows the annualized recurring costs.

Table 5: Annual Sustaining Cost For Single ANSI Pump

ANSI Pump:

Cost Element	MTBF, years	Failures per year or activity per yr	Elapsed Repair or Activity hours	Activity Cost US$/hr	Cost For Lab.,Exp., & Matl US$	Part Cost US$	Logistics Cost US$ per incident	Lost Gross Margin US$	Electrical Power Costs US$	Total Cost US$/yr
Electricity	--	–	--					–	$ 16,500	$ 16,500
Seal	3	0.3333	8	100	$ 267	$ 600	$ 50	$ 10,667		$ 11,583
Shaft	18	0.0556	10	100	$ 56	$ 239	$ 25	$ 2,222		$ 2,542
Impeller	12	0.0833	8	100	$ 67	$ 400	$ 38	$ 2,667		$ 3,171
Housing	18	0.0556	14	100	$ 78	$ 267	$ 64	$ 3,111		$ 3,519
Pump Bearings	4	0.2500	8	100	$ 200	$ 450	$ 38	$ 8,000		$ 8,688
Motors	12	0.0833	8	100	$ 67	$ 250	$ 42	$ 2,667		$ 3,025
Coupling	8	0.1250	8	100	$ 100	$ 50	$ 38	$ 4,000		$ 4,188
Maintenance PM visits			12	50	$ 600					$ 600
Operations PM visits			10.4	35	$ 364					$ 364
Vibration Dept			10.4	50	$ 520					$ 520
Training costs			0.5	255	$ 128					$ 128
Total					**$ 2,445**	**$ 2,256**	**$ 293**	**$ 33,333**	**$ 16,500**	**$ 54,827**

	Item Cost US$	Logistics Cost US$
Seal cost=	$ 1,500	$ 75
Bearings cost=	$ 300	$ 75
Shaft cost=	$ 2,500	$ 300
Impeller cost=	$ 3,000	$ 300
Pump housing=	$ 3,000	$ 1,000
Motor cost=	$ 3,000	$ 500
Coupling cost=	$ 400	$ 300
Lost gross margin US$/hr =	$ 4,000	
Power cost(US$165/hp-yr)=	$ 165	
Motor size(hp)=	100	

System failure rate= 0.9861
System MTBF= 1.01408

1 yr reliability, R= 37%
1 yr unreliability, UR= 63%
1 yr Availability, A= 0.999

Good maintenance practice:
Seal replacement = seals+bearings
Bearing replacement=seals+bearings
Shaft replacement=shaft+seals+bearings
Impeller replacement=impeller+seals+bearings
Housing replacement=housing+seals+bearings

A quick cost review of the single ANSI pump shows lost gross margin from outages is the biggest annual cost problem as shown in Table 5 for a sustaining cost of US$ 54,827/year. The ANSI pump will consume 16.7 corrective and 35.8 preventive manhours each year.

Use of MTBFs and expected failures are based on the exponential distribution which is an acceptable first-cut for costs, but this technique is not an accurate predictor of failures for wear-out phenomena expected for many of these components. An improved accuracy method will be described later using Weibull distributions for failures.

Alternative #2-Add redundant ANSI pump: Use the following details from plant experience—

This case results in pumps installed in parallel but operated as a standby redundant system as the redundant components are not energized but are literally standing by waiting to be used when failure of the operating system is detected—of course the detection/switching device is very important for calculating overall system reliability and for this case the reliability is assumed to be 100%. Also for simplicity, the reliability of the system is calculated as if the redundant pumps are operating in parallel. Furthermore, experience in most chemical plants and refineries shows impending failure is usually detected and redundant systems are usually started in a timely manner to avoid lost production from the failing device—so assume no loss of production by use of redundant pumps.

Capital cost for the redundant ANSI pump are $8000 plus $3000 for check/isolation valves, plus $2500 for construction and installation along with US$1000 for program management, US$1500 for engineering design, and US$1000 for documentation. Likewise the plant maintenance organization will incur US$1000 for engineering documentation costs to put the equipment into the paperwork system.

Lost gross margin occurs at US$4000/hour when the process is down for repairs.

Annual power cost for running the pump is US$165/yr per horsepower—remember either the old pump runs or the new pump (not both at the same time). The plant incurs 1.6 power outages each year for an average downtime of 0.5 hours and this cost is charged into plant overhead rather than to individual pieces of equipment.

Annual power costs are: (US$165/hp-yr)*(100 hp) = US$16500.

Assume no lost production time by use of the redundant pumps. Keep all other costs as described for the single ANSI pump and depreciate the assets over the 10 year project life.

Disposal costs occur as a lump at the end of the ten year remaining life are expected to be: US$500 for permits and legal costs associated with disposition, US$500 for wrecking/disposal costs, US$1000 for remediation costs, US$0 for write-off/recovery costs, and US$1000 estimated green/clean costs associated with disposal of the asset. These costs will occur in the final year. Table 6 shows non-annualized acquisition and sustaining costs for the parallel ANSI pumps.

Table 6: Non-annualized Acquisition And Sustaining Costs For Parallel ANSI Pumps

Parallel/Redundant ANSI Pumps:

Cost Element	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition Costs:											
Program Management	1000										
Engineering Design	1500										
Engineering Data	0										
Spare parts & Logistics	0										
Facilities & Construction	0										
Initial Training	0										
Technical Data	0										
Capital Equipment	13500										
Sustaining Costs:											
Documentation Costs	1000	0									
Disposal Costs											3000
Total =	17000	0	0	0	0	0	0	0	0	0	3000

Table 7 shows the annualized recurring costs for parallel/redundant ANSI Pumps.

Table 7: Annual Costs For Parallel/Redundant ANSI Pumps

Parallel/Redundant ANSI Pumps:

Cost Element	MTBF, years	Failures per year or activity per yr	Elapsed Repair or Activity hours	Activity Cost US$/hr	Cost For Lab.,Exp., & Matl US$	Part Cost US$	Logistics Cost US$ per incident	Lost Gross Margin US$	Electrical Power Costs US$	Total Cost US$/yr
Electricity	--	–	--						$ 16,500	$ 16,500
Seal	3	0.3333	8	100	$ 267	$ 600	$ 50			$ 917
Shaft	18	0.0556	10	100	$ 56	$ 239	$ 25			$ 319
Impeller	12	0.0833	8	100	$ 67	$ 400	$ 38			$ 504
Housing	18	0.0556	14	100	$ 78	$ 267	$ 64			$ 408
Pump Bearings	4	0.2500	8	100	$ 200	$ 450	$ 38			$ 688
Motors	12	0.0833	8	100	$ 67	$ 250	$ 42			$ 358
Coupling	8	0.1250	8	100	$ 100	$ 50	$ 38			$ 188
Maintenance PM visits			12	50	$ 600					$ 600
Operations PM visits			10.4	35	$ 364					$ 364
Vibration Dept			10.4	50	$ 520					$ 520
Training costs			0.5	255	$ 128					$ 128
Total					**$ 2,445**	**$ 2,256**	**$ 293**	**$ -**	**$ 16,500**	**$ 21,493**

	Item Cost US$	Logistics Cost US$
Seal cost=	$ 1,500	$ 75
Bearings cost=	$ 300	$ 75
Shaft cost=	$ 2,500	$ 300
Impeller cost=	$ 3,000	$ 300
Pump housing=	$ 3,000	$ 1,000
Motor cost=	$ 3,000	$ 500
Coupling cost=	$ 400	$ 300
Lost gross margin US$/hr =	$ 4,000	
Power cost(US$165/hp-yr)=	$ 165	
Motor size(hp)=	100	

System failure rate= 0.9861
System MTBF= 1.01408

1 yr reliability, R= 61%
1 yr unreliability, UR= 39%
1 yr Availability, A= 0.9999+

Good maintenance practice:
Seal replacement = seals+bearings
Bearing replacement=seals+bearings
Shaft replacement=shaft+seals+bearings
Impeller replacement=impeller+seals+bearings
Housing replacement=housing+seals+bearings

A quick cost review of the redundant ANSI pump shows electrical power costs are the biggest annual cost problem shown in Table 7 for a sustaining cost of US$ 21,493/year.

Alternative #3-Replace Solo ANSI pump With Solo API Pump: Use the following details from plant experience—

Capital costs are $18000 for a solo API pump plus $3500 for construction and installation along with US$1000 for program management, US$1500 for engineering design, US$1000 for documentation, and US$500 for technical data. Likewise the plant maintenance organization will incur US$1000 for engineering documentation costs to put the equipment into the paperwork system and US$1500 for training costs associated with the new class of equipment. Spare parts for the new equipment will be increased by $2900 for a new set of seals and bearings.

Lost gross margin occurs at US$4000/hour when the process is down for repairs. Costs will be charged for each specific case using the accounting principle that cost follows activity.

Annual power cost for running the pump is US$165/yr per horsepower. The plant incurs 1.6 power outages each year for an average downtime of 0.5 hours and this cost is charged into plant overhead rather than to individual pieces of equipment.

Annual power costs are: (US$165/hp-yr)*(100 hp) = US$16500.

See Table 6 for other failure details and plan to depreciate the assets over the 10 year project life.

Disposal costs will occur as a lump sum cost at the end of the ten year remaining life are expected to be: US$500 for permits and legal costs associated with disposition, US$500 for wrecking/disposal costs, US$1000 for remediation costs, US$0 for write-off/recovery costs, and US$1000 estimated green/clean costs associated with disposal of the asset. These disposal costs will occur in the final year. Table 8 shows non-annualized acquisition and sustaining costs for a new solo API pump.

Table 8: Non-annualized Acquisition And Sustaining Costs For A New Solo API Pump

API Pump:

Cost Element	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Acquisition Costs:											
Program Management	1000										
Engineering Design	1500										
Engineering Data	1000										
Spare parts & Logistics	2900										
Facilities & Construction	3500										
Initial Training	1500										
Technical Data	500										
Capital Equipment	18000										
Sustaining Costs:											
Documentation Costs	1000	0									
Disposal Costs											3000
Total =	30900	0	0	0	0	0	0	0	0	0	3000

Table 9: shows the annualized recurring costs for parallel/redundant ANSI Pumps.

Table 9: Annual Sustaining Costs For API Pump

API Pump:

Cost Element	MTBF, years	Failures per year or activity per yr	Elapsed Repair or Activity hours	Activity Cost US$/hr	Cost For Lab.,Exp., & Matl US$	Part Cost US$	Logistics Cost US$ per incident	Lost Gross Margin US$	Electrical Power Costs US$	Total Cost US$/yr
Electricity	--	–	--					–	$ 16,500	$ 16,500
Seal	4.5	0.2222	8	100	$ 178	$ 644	$ 33	$ 7,111		$ 7,967
Shaft	22	0.0455	10	100	$ 45	$ 291	$ 20	$ 1,818		$ 2,175
Impeller	16	0.0625	8	100	$ 50	$ 400	$ 28	$ 2,000		$ 2,478
Housing	22	0.0455	14	100	$ 64	$ 336	$ 52	$ 2,545		$ 2,998
Pump Bearings	6	0.1667	8	100	$ 133	$ 483	$ 25	$ 5,333		$ 5,975
Motors	12	0.0833	8	100	$ 67	$ 250	$ 42	$ 2,667		$ 3,025
Coupling	20	0.0500	8	100	$ 40	$ 60	$ 15	$ 1,600		$ 1,715
Maintenance PM visits			12	50	$ 600					$ 600
Operations PM visits			10.4	35	$ 364					$ 364
Vibration Dept			10.4	50	$ 520					$ 520
Training costs			0.5	255	$ 128					$ 128
Total					**$ 2,188**	**$ 2,465**	**$ 216**	**$ 23,075**	**$ 16,500**	**$ 44,444**

	Item Cost US$	Logistics Cost US$
Seal cost=	$ 2,500	$ 75
Bearings cost=	$ 400	$ 75
Shaft cost=	$ 3,500	$ 300
Impeller cost=	$ 3,500	$ 300
Pump housing=	$ 4,500	$ 1,000
Motor cost=	$ 3,000	$ 500
Coupling cost=	$ 1,200	$ 300
Lost gross margin US$/hr =	$ 4,000	
Power cost(US$165/hp-yr)=	$ 165	
Motor size(hp)=	100	

System failure rate= 0.6756
System MTBF= 1.4801

1 yr reliability, R= 51%
1 yr unreliability, UR= 49%
1 yr Availability, A= 0.999

Good maintenance practice:
Seal replacement = seals+bearings
Bearing replacement=seals+bearings
Shaft replacement=shaft+seals+bearings
Impeller replacement=impeller+seals+bearings
Housing replacement=housing+seals+bearings

A quick cost review for the solo API pump shows lost gross margin from outages is still the biggest annual cost problem (just as it was for the ANSI pump) as shown in Table 9 for a sustaining cost of US$

44,444/year. The API pump will consumer 11.5 corrective (5.2 hours less than an ANSI pump) and 35.8 preventive (no difference from ANSI) manhours each year.

Step 6: Make cost profiles for each year of study.

This step will take into account the annualized charges shown above in Tables 4, 5, and 6 plus the lumped charges at the front and rear end of the project as shown in Table 10.

Table 10: Summary Of Cost Profiles For Each Alternative

	Year										
	0	1	2	3	4	5	6	7	8	9	10
Alternative #1-Existing Solo ANSI Pump											
Capital	0										
Cost		57827	57827	57827	57827	57827	57827	57827	57827	57827	60827
Savings		0	0	0	0	0	0	0	0	0	0
Depreciation	0	0	0	0	0	0	0	0	0	0	0
Profit b/4 taxes		-57827	-57827	-57827	-57827	-57827	-57827	-57827	-57827	-57827	-60827
Tax Provision		21974	21974	21974	21974	21974	21974	21974	21974	21974	23114
Net Income		-35853	-35853	-35853	-35853	-35853	-35853	-35853	-35853	-35853	-37713
Add Back Depreciation		0	0	0	0	0	0	0	0	0	0
Cash Flow	0	-35853	-35853	-35853	-35853	-35853	-35853	-35853	-35853	-35853	-37713
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11
Present Value	0	-32011	-28582	-25519	-22785	-20344	-18164	-16218	-14480	-12929	-12142
Net Present Value	**$ (203,175)**	using a 12% discount rate									
Alternative #2-Add Parallel/Redundant ANSI Pump											
Capital	13500										
Cost	3500	21493	21493	21493	21493	21493	21493	21493	21493	21493	24493
Savings		0	0	0	0	0	0	0	0	0	0
Depreciation		1350	1350	1350	1350	1350	1350	1350	1350	1350	1350
Profit b/4 taxes		-22843	-22843	-22843	-22843	-22843	-22843	-22843	-22843	-22843	-25843
Tax Provision		8680	8680	8680	8680	8680	8680	8680	8680	8680	9820
Net Income		-14163	-14163	-14163	-14163	-14163	-14163	-14163	-14163	-14163	-16023
Add Back Depreciation		1350	1350	1350	1350	1350	1350	1350	1350	1350	1350
Cash Flow	-17000	-12813	-12813	-12813	-12813	-12813	-12813	-12813	-12813	-12813	-14673
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11
Present Value	-17000	-11440	-10214	-9120	-8143	-7270	-6491	-5796	-5175	-4620	-4724
Net Present Value	**$ (89,993)**	using a 12% discount rate									
Alternative #3-Replace ANSI Pump With Solo API Pump											
Capital	18000										
Cost	12900	44444	44444	44444	44444	44444	44444	44444	44444	44444	47444
Savings		0	0	0	0	0	0	0	0	0	0
Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Profit b/4 taxes		-46244	-46244	-46244	-46244	-46244	-46244	-46244	-46244	-46244	-49244
Tax Provision		17573	17573	17573	17573	17573	17573	17573	17573	17573	18713
Net Income		-28671	-28671	-28671	-28671	-28671	-28671	-28671	-28671	-28671	-30531
Add Back Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Cash Flow	-30900	-26871	-26871	-26871	-26871	-26871	-26871	-26871	-26871	-26871	-28731
Discount Factors	1.00	1.12	1.25	1.40	1.57	1.76	1.97	2.21	2.48	2.77	3.11
Present Value	-30900	-23992	-21422	-19126	-17077	-15247	-13614	-12155	-10853	-9690	-9251
Net Present Value	**$ (183,328)**	using a 12% discount rate									

Based on these alternatives, adding the ANSI pump in parallel looks more attractive based on the NPV at the 12% discount rate using straight line depreciation. No revenue stream is included in these calculations so the case with the smallest loss will be the most attractive case.

Remember each company will have it's favorite discount rate, depreciation schedule, and method for making capital decisions. That means local conditions may prevail in making decisions.

Step 7: Make break-even charts for alternatives.

Breakeven charts are useful tools for showing effects of fixed and variable costs. Results for the three alternatives are shown in Figure 12 for a quick grasp of how the breakeven points compare to the base case.

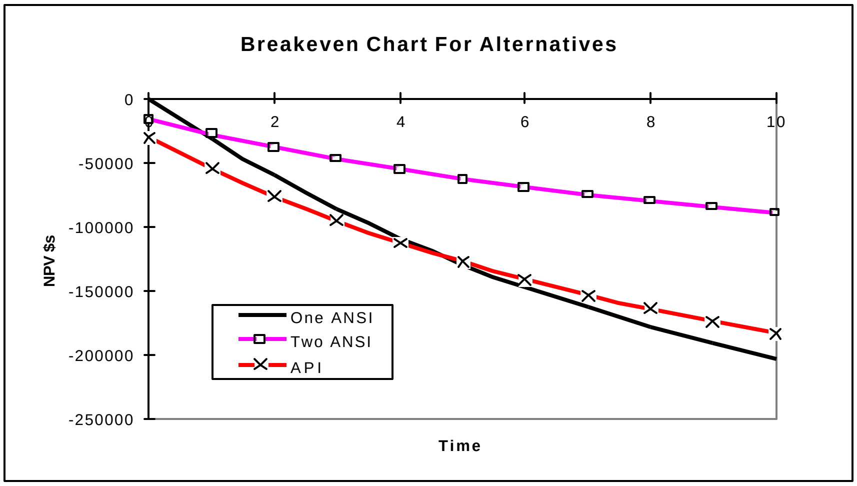


Figure 12: Breakeven Chart

Cumulative present values are shown on the y-axis to combine cost of money with time and show how the effects of expenditures and cost reductions play together. Of course the issue is to choose alternatives which payback quickly and payback big returns!

The parallel ANSI pump cost line crosses the datum line for the solo ANSI pump in ~1 year so the costs are less for the redundant system after passing the one year mark. The solo API pump crosses the datum line in ~5 years and the cost are less than the solo ANSI pump but the redundant ANSI pump system continues to have a smaller cost and thus is more desirable.

Step 8: Pareto charts of vital few cost contributors.

The purpose of Pareto charts is to identify the vital few cost contributors so the details can be itemized for sensitivity analysis and ignore the trivial many issues. Pareto rules say that 10 to 20% of the elements of a cost analysis will identify 60% to 80% of the total cost—these items are the vital few items of concern and need to be carefully considered.

The cost elements for the solo ANSI pump are shown in Figure 13 with the high cost of lost gross margins more than twice the cost of the next item. Compare the absolute magnitude of the costs with the cost elements for Figures 13, 14, and 15.

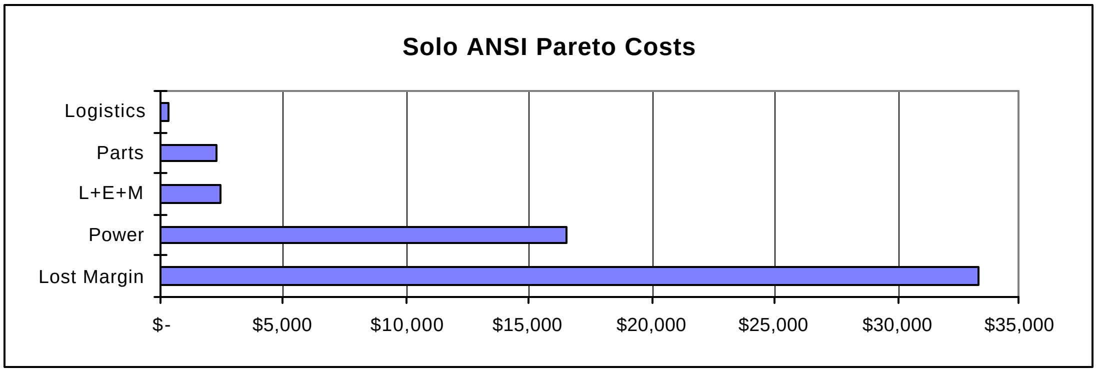


Figure 13: Pareto Cost Chart For Solo ANSI Pump

When redundant ANSI Pumps are installed, the Pareto chart looks substantially different as shown in Figure 14 where electrical power becomes the most significant cost item.

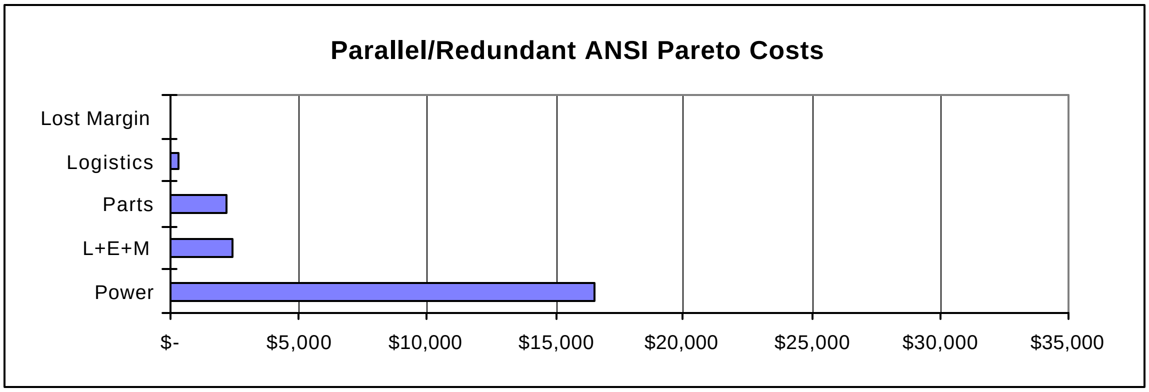


Figure 14: Pareto Cost Chart For Parallel/Redundant Pumps

When a API pump is substituted for the ANSI pump, the Pareto cost look similar to Figure 13 but the magnitude is different as shown in Figure 15.

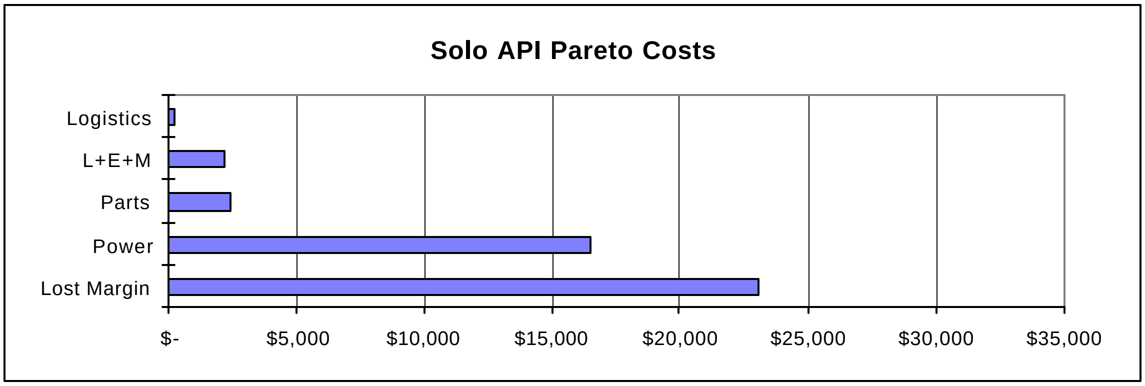


Figure 15: Pareto Cost Chart For Solo API Pump

Step 9: Prepare sensitivity analysis of high costs and reasons for high cost.

Sensitivity analysis allows study of key parameters on LCC. In Table 5 the analysis begins with mean time between failures which drives the failure rate. Since all of the components are in series, the failure rates for the exponential distribution can be added to obtain an overall failure rate for the system. Figure 13 shows the key for controlling cost is to avoid the downtime which results in lost gross margin caused by unreliability.

Unreliability can be reduced by using a higher grade pump as shown in Figure 15, or the penalty of lost gross margin is avoided by using a redundant pump as shown in Figure 14. Of course small incremental reductions in lost margin can be achieved by performing the repair work faster—this is frequently the spur rammed into the side of the maintenance organization. Unfortunately the incremental gains achieved by the faster repairs is very small compared to using a redundancy strategy which leap-frogs the problem and makes major reductions in lost margins as shown in Figure 14. Many industrial organizations concentrate on small incremental gains of working faster (feels good but isn't too effective) rather than using a smarter reliability strategy to avoid the breakdowns (preventing the problem rather than providing efficient first aid responses) which are the root cause for loss of gross margins.

One issue is hidden in Figures 13 and 15 raises its head in Figure 14—it's the cost of electrical power to drive the pump. Power consumed is a direct result of work performed, energy lost in inefficient motors/bearing, and energy lost in pump dynamics. Energy savings by use of high efficiency motors can save 2-5% of the total power cost, and choosing high efficiency internals for the pumps can save 5-10% of the total power cost. In short, purchase high efficiency motors and high efficiency internals carefully matched to the task to achieve a short payback period. If pump internals were selected for 80% pump efficiency rather than the 70% efficiency used for the calculations, the lower power consumed would be US$16500*(70%/80%) = $14438 which results in a savings of US$2062 each year—or about equal to all maintenance labor efforts spent to correct failures!!! The point is this: examining cost reduction possibilities by use of LCC details can be productive for discovering real savings opportunities rather than following the old recipes—in short, creating wealth for stockholders often means **stop** doing some things the old way and **start** doing new things in smarter ways.

Using the overall ANSI pump failure rates and a mission time of one year, the reliability at the end of one year is calculated as 37% (which is about the same as saying one pump in three will operate for a one year interval without some type of failure). The chance for failure free intervals is low. Much of this poor reliability is driven by how the pump is operated. If the pump manufacture ran factory tests for this pump, the pump would demonstrate much higher reliability (i.e., a lower failure rate) because it would be operated continuously at optimum conditions. Optimum conditions are rarely achieved in production plants because of variations in operating conditions and operating styles.

If the philosophy of the operating group is "…all pumps cavitate…" then reliability within the plant will be low as equipment will be killed before it reaches its inherent life span. Figure 16 illustrates the sensitivity of pump reliability to pump curves and other well known problems. The shape of the reliability curve is dependent upon many pump features and operating conditions.

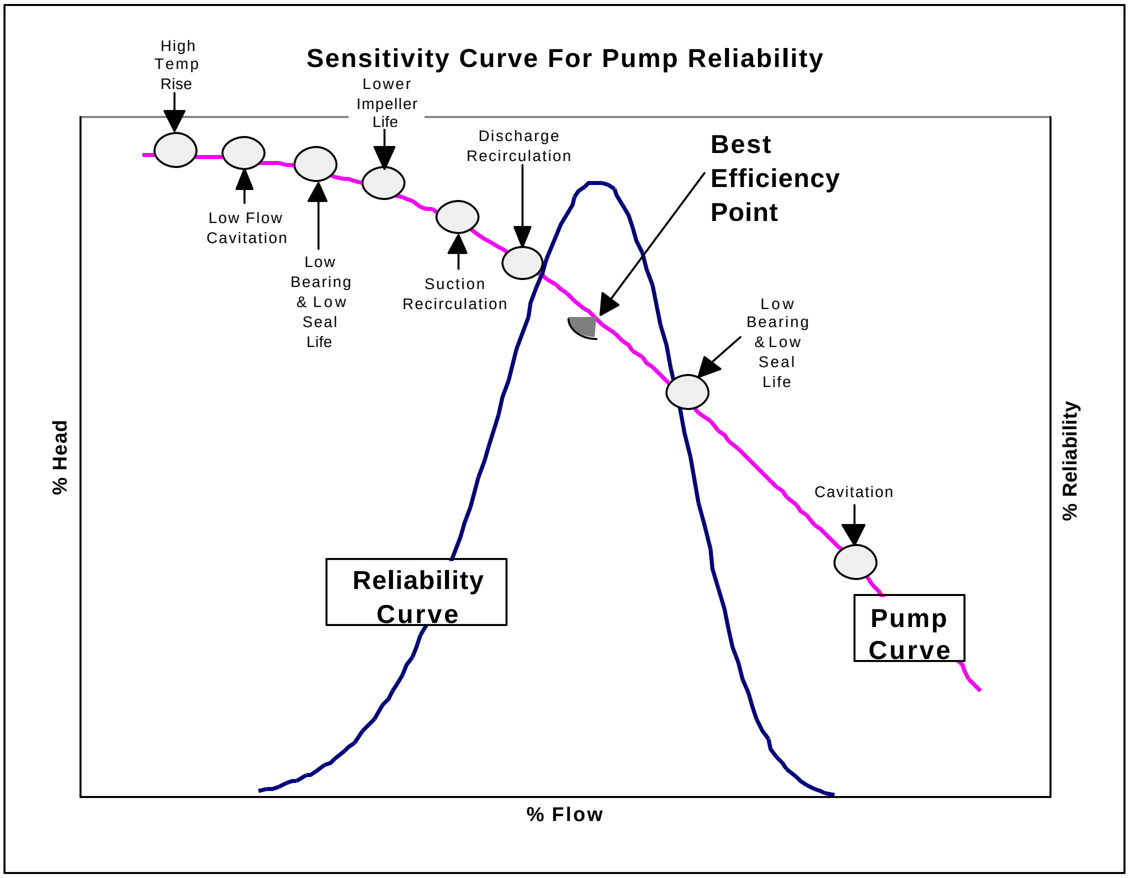


Figure 16: Pump Reliability vs Pump Curve

Figure 17 shows other possible sensitivity studies which combine multiple features.

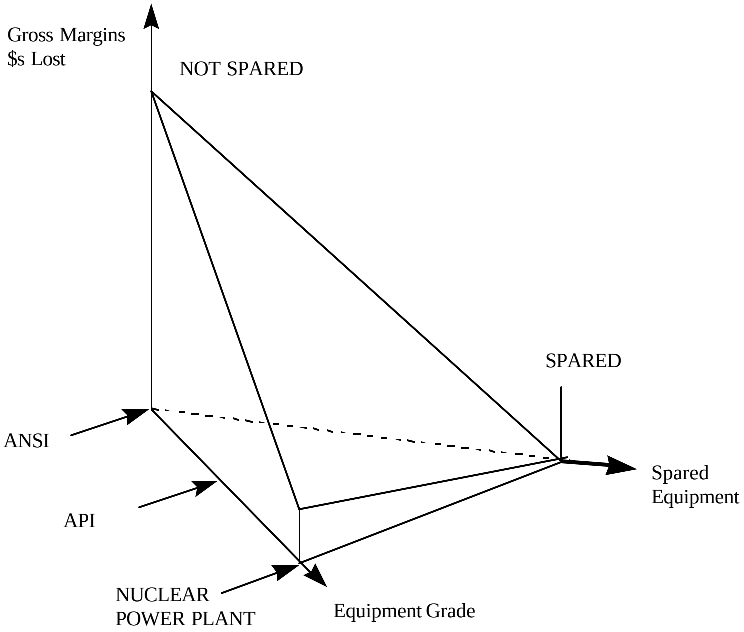


Figure 17: Various Inputs vs Lost Gross Margin $s

Of course the effectiveness equation offers good information as the largest single variable is reliability as other components of the effectiveness equation in Table 11 have minor variations.

Table 11: Alternatives Versus Effectiveness And LCC=NPV

Parameter	Solo ANSI Pump	Dual ANSI Pump	Solo API Pump
Availability	0.999	0.9999	0.9993
Reliability	0.37	0.61	0.51
Maintainability	0.8 estimated	0.8 estimated	0.8 estimated
Capability	0.8 estimated	0.8 estimated	0.8 estimated
System Effectiveness	0.2366	0.3904	0.3262
Life Cycle Cost	-$203,175	-$89,993	-$183,328

The life cycle cost shown in Figure 8 is the NPV results of the alternatives to put LCC into business terms.

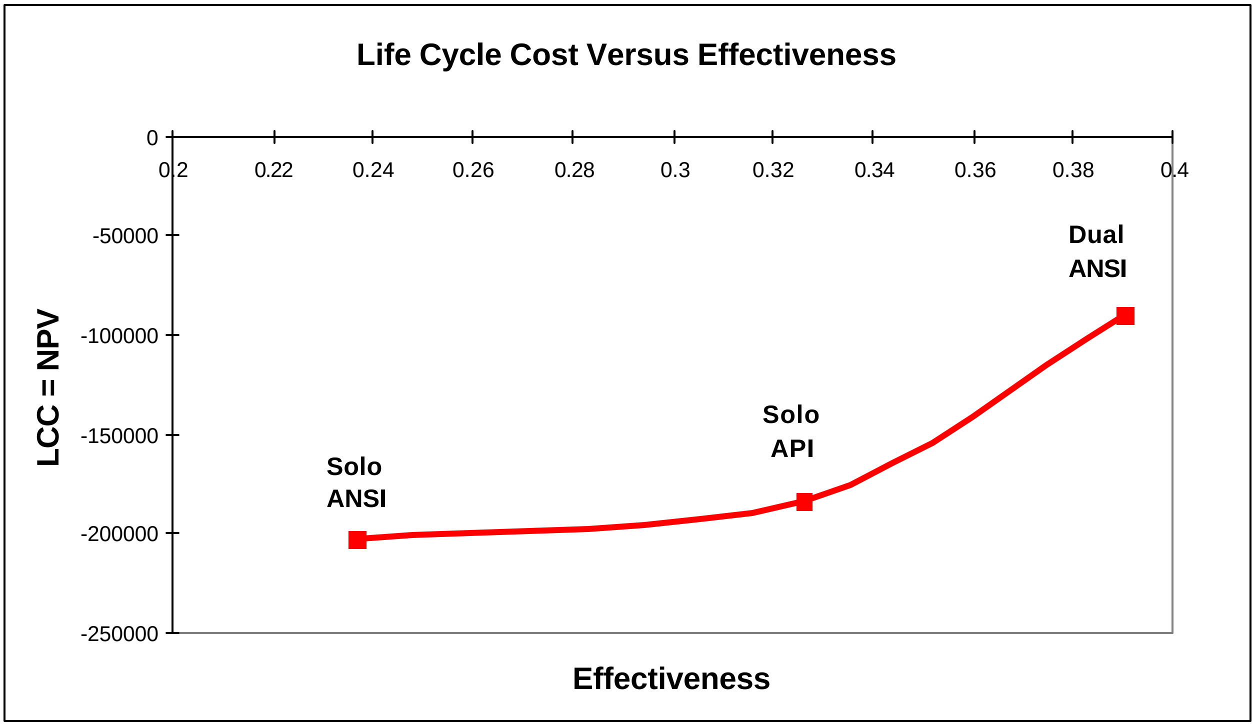


Figure 8: LCC and System Effectiveness

The shape of the curve is decided by selection of alternatives and cost drivers.

Step 10: Study risks of high cost items and occurrences.

Failure data is available from many sources to test if the assumptions made in the analysis are valid or if unusual risks have been taken with numbers used in the study. Consider the following failure rate values (Bloch 1994) or (Bloch 1995):

Table 12: Failure Data Converted to Mean Time Between Failures

	Failure rate (failures/10^6 hours)		**MTBF (years)**	
Item	Low	High	Low	High
Ball Bearings	4	70	1.6	28.5
Couplings	3	40	2.9	38.0
Housing				
Impeller	0.7	8	14.3	163
Motors	5	900	0.1	22.8
Seals	20	30	3.8	5.7
Shafts	3	20	5.7	38.1

An example of the conversion from failure rates to mean time between failures is:

MTBF = 1/((4E-06 failures/hour)*(8760 hours/year)) = 28.5 years

Compare Table 12 to Table 5 and Table 7 for ANSI pumps and the data looks comparable except that the failure rate for impellers may have been selected too high and thus the MTBF is lower than shown in Table 12—let local operating conditions and experience decide the correct value. Comparing Table 12 to Table 9 for the API pump, the results look OK.

So, from where did the failure rate for the pump housing come? Use experience or other sources—one stop shopping for failure rates is not possible!

Select cost data from local plant experiences or proposed cost structures for new plants.

Step 11: Select preferred course of action using LCC.

The selection of a parallel/redundant strategy using ANSI pumps is the most attractive alternative out of the three proposed because it avoids process failure and thus reduces the high cost of <u>un</u>reliability. Buy equipment which is electrical power efficient and correctly sized with high hydraulic efficiency to make substantial reductions in electrical power consumption which is usually a hidden cost item but clearly identified by LCC as a vital element.

ADDING UNCERTAINTY TO THE LCC RESULTS

Each element in the above LCC computation is uncertain. Nothing fails on schedule. Nothing is repaired in exactly the same time interval. Seldom are costs for acquiring goods and services the same price each time. Furthermore, experience tells us that knowledge of failure modes for equipment is required to make best use of reliability centered maintenance (RCM) strategies. Uncertainty requires the use of statistical distributions in addition to the usual arithmetic.

Most engineers know about normal (Gaussian) statistical distributions which employ a mean value, x-bar, to describe central tendencies and a standard deviation, σ, to describe scatter in the data. A better statistical distribution for explaining the life and repair times for equipment are Weibull distributions (Abernethy 1996) with a shape factor, β (similar to σ), and a characteristic life, η.

Statistical distributions give a different value every time data is drawn for solving spreadsheet problems because of chance selections. Thus Monte Carlo simulation techniques are used to join probability distributions and economic data to solve problems of uncertainty using spreadsheet techniques (Barringer

1996a). Monte Carlo simulation techniques use random numbers to generate failure data and cost data considering the statistical distributions. Monte Carlo results are similar to real life because the results have variations around a given theme.

Monte Carlo results are used with common spreadsheet programs such as Excel™ or Lotus™. Or specialized add-in programs such as @Risk™ can add uncertainty to the calculations. Instead of producing a single answer, the Monte Carlo results provide a central trend while providing an idea about the expected variations that may result from many interactions. Ideas about the variations in results are obtained by repeating the Monte Carlo trials many times and studying the end results. With fast PCs on most every engineers desk, it is possible to conduct 10000 iterations of a complicated spreadsheet in only a few minutes at a very low cost.

A flag was raised in Alternative #1 section about exponential failure distributions. With the exponential distribution the chance for failure is uniform for each period and this does not conform to equipment expectations where wear-out failure modes may predominate with their increasing failure rates as equipment ages. Weibull failure database information is available (Barringer 1996b) to supplement earlier mentioned failure data from Bloch and Geitner. A partial listing of the Weibull database is shown in Table 13. Recent papers describe how to put the Weibull database information to work (Weber 1996).

Table 13: Typical Weibull Failure Data

	Beta Values (Weibull Shape Factors)			**Eta Values (Weibull Characteristic Life—hrs)**		
	Low	Typical	High	Low	Typical	High
Item						
Ball Bearings	0.7	1.3	3.5	14000	40000	250000
Couplings	0.8	2	6	25000	75000	333000
Housing						
Impeller	0.5	2.5	6	125000	150000	1400000
Motors	0.5	1.2	3	1000	100000	200000
Seals	0.8	1.4	4	3000	25000	50000
Shafts	0.8	1.2	3	50000	50000	300000

Here's how the Weibull database and Monte Carlo simulations work using the coupling data as an example. Given $\beta = 2.0$, and $\eta = 75{,}000$ hours, what is a Monte Carlo age to failure? Solving the Weibull equation for time,

$$t = \eta * \{\ln(1/(1\text{-CDF}))\}^{\wedge}(1/\beta)$$

where CDF is the cumulative distribution function which always varies between 0 and 1. The CDF range is convenient because spreadsheets also have a random number function which varies between 0 and 1. This means if the CDF = (chosen by a number between 0 and 1) = 0.3756, then the Weibull age to failure is 51,470 hours (or 5.9 years) as driven by the random choice of the number 0.3756. Contrast the Weibull results for age-to-failure with results from the exponential distribution, ($\beta = 1$) age-to-failure which produces 35,322 hours or (4.0 years) using the same random number. When the random numbers are used over and over, then specific ages to failure are selected as representative of specific ages-to-failure.

Table 14 Shows how Monte Carlo simulation works for the unspared ANSI pump.

- In section (a), the Weibull values are used with random numbers to draw a random age-to-failure. Other ages-to-failure are propagated across the 10 year study period showing how many failures are expected for each year of the study (and multiple failures for an item can occur in a period). The student has the opportunity to modify the scenario and accompanying logic statements to build more complex failure propagation tables taking into account how good maintenance practices will reduce the number of failures occurring each period.
- In section (b), the numbers of failures are added for cumulative failure results.
- In section (c) the cumulative failures are normalized to an annual basis.
- In section (d), costs are added to the failures and the costs are slightly overstated because costs for good maintenance practices are included even with the slightly elevated failure rates noted above for section (a). Compare annual costs of Table 14 with the results from Table 5.

Why spend the time and effort building such complicated analysis schemes? The time required to construct Table 14 was ~10 hours and run time was 2.6 hours for 10,000 iterations on a 486/50MHz computer, and 17 minutes for a Pentium Pro 200MHz. Monte Carlo simulations are more correct than the generalized and simplified data. The Excel spreadsheet from Table 14 is available for download from the world wide web (Barringer 1996c), and it can serve as guide for building more complicated analysis to obtain more accurate LCC information.

Table 14: Monte Carlo Simulation

Unspared ANSI Pump Life-Cycle Cost Simulation In An Excel Spreadsheet

a) Individual Iteration

				Project Year Of Replacement And Number Of Replacements Required									
Cost Element	η	β	1st Age To Failure	1	2	3	4	5	6	7	8	9	10
Electricity													
Seal	3	1.4	0.23	2	0	0	2	1	0	0	1	0	2
Shaft	18	1.2	33.96	0	0	0	0	0	0	0	0	0	0
Impeller	12	2.5	9.19	0	0	0	0	0	0	0	0	0	1
Housing	18	1.3	12.71	0	0	0	0	0	0	0	0	0	0
Pump Bearings	4	1.3	1.97	0	1	0	0	0	0	1	1	0	0
Motors	12	1.2	5.26	0	0	0	0	0	1	0	0	0	0
Coupling	8	2.0	8.11	0	0	0	0	0	0	0	0	1	0
Hours Down Time =				16.00	8.00	0.00	16.00	8.00	8.00	8.00	16.00	8.00	24.00
Number Of Failures=				2	1	0	2	1	1	1	2	1	3

b) Cum. Iterations--> 10002

				Project Year Of Replacement And Cumulative Number Of Replacements Required									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity													
Seal	3	1.4		2038	3018	3462	3644	3644	3703	3653	3613	3643	3738
Shaft	18	1.2		313	405	436	443	465	495	533	541	540	584
Impeller	12	2.5		9	80	190	318	450	586	681	795	876	992
Housing	18	1.3		247	342	376	425	462	477	499	546	552	526
Pump Bearings	4	1.3		1676	2193	2507	2582	2610	2591	2711	2658	2754	2708
Motors	12	1.2		508	631	724	733	756	785	788	897	810	890
Coupling	8	2.0		141	431	757	959	1153	1345	1338	1445	1458	1438
Cumulative Hours Down Time =				41564	59662	70744	76268	80022	83708	85684	88318	89456	91332
Cumulative Number of Failures=				4932	7100	8452	9104	9540	9982	10203	10495	10633	10876

c) Annual Failures Expected

				Project Year And Average Number Of Failures Required Each Year									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity													
Seal	3	1.4		0.204	0.302	0.346	0.364	0.364	0.370	0.365	0.361	0.364	0.374
Shaft	18	1.2		0.031	0.040	0.044	0.044	0.046	0.049	0.053	0.054	0.054	0.058
Impeller	12	2.5		0.001	0.008	0.019	0.032	0.045	0.059	0.068	0.079	0.088	0.099
Housing	18	1.3		0.025	0.034	0.038	0.042	0.046	0.048	0.050	0.055	0.055	0.053
Pump Bearings	4	1.3		0.168	0.219	0.251	0.258	0.261	0.259	0.271	0.266	0.275	0.271
Motors	12	1.2		0.051	0.063	0.072	0.073	0.076	0.078	0.079	0.090	0.081	0.089
Coupling	8	2.0		0.014	0.043	0.076	0.096	0.115	0.134	0.134	0.144	0.146	0.144
Average Down Time Hours =				4.16	5.97	7.07	7.63	8.00	8.37	8.57	8.83	8.94	9.13
Average Number Of Failures=				0.49	0.71	0.85	0.91	0.95	1.00	1.02	1.05	1.06	1.09

d) Annual Cost Expected For Each Time Interval

				Project Year And Annual Costs Expected From Simulation									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity	--	–		16500	16500	16500	16500	16500	16500	16500	16500	16500	16500
Seal	3	1.4		7081	10485	12028	12660	12660	12865	12692	12553	12657	12987
Shaft	18	1.2		1432	1853	1994	2026	2127	2264	2438	2475	2470	2671
Impeller	12	2.5		34	304	723	1210	1712	2229	2591	3024	3333	3774
Housing	18	1.3		1564	2166	2381	2692	2926	3021	3161	3458	3496	3332
Pump Bearings	4	1.3		5823	7619	8710	8971	9068	9002	9419	9235	9568	9408
Motors	12	1.2		1844	2290	2628	2660	2744	2849	2860	3255	2940	3230
Coupling	8	2.0		546	1670	2933	3715	4467	5211	5184	5598	5649	5571
Maintenance PM visits				$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600
Operations PM visits				$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364
Vibration Dept				$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520
Training costs				$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128
Total				**$36,435**	**$44,499**	**$49,509**	**$52,046**	**$53,816**	**$55,553**	**$56,455**	**$57,710**	**$58,224**	**$59,085**

Approximate system failure rate (failures/yr)=	0.493	0.710	0.845	0.910	0.954	0.998	1.020	1.049	1.063	1.087
Approximate system MTBF(years/failure) =	2.03	1.41	1.18	1.10	1.05	1.00	0.98	0.95	0.94	0.92
Theoretical 1 yr Reliability =	60.5%									
1 yr reliability, R=	61.1%	49.2%	43.0%	40.2%	38.5%	36.9%	36.1%	35.0%	34.5%	33.7%
1 yr Availability, A=	99.95%	99.93%	99.92%	99.91%	99.91%	99.90%	99.90%	99.90%	99.90%	99.90%

What different information was obtained from the Monte Carlo simulation? From the annualized failure data, the rhythms of expected repairs are observed and the cost of outages is more accurately predicted. Clearly the uncertainty of failures has been used to generate cost numbers. Notice the number of seal failures and bearing failures are approximately the same which justifies the usual good maintenance practice of replacing both units when either fails. Also notice the close agreement between the theoretical reliability and simulated reliability. Likewise note how the one year reliability values decline as the system ages which parallels operating experience and common sense but is often difficult to prove with numbers.

The simulation shows availability drops slightly over the 10 year interval but the number of failures approximately doubles due to system age—consequently the reliability plunges (remember availability and reliability are not the same measurement!!). Clearly more failures results in higher maintenance costs and the substantial decline in reliability.

When performing iterations manually (by pressing the F9 key for the Excel spreadsheet), notice occasions when seals or bearings will incur two failures in the same yearly interval—just as sometimes occurs in real life. Also studying the spreadsheet using the audit tool from the Excel menu will make the calculation scenario understandable. The student can modify the spreadsheet as required to make the results "real life" rather than rely on the magic of the computer. Remember this scenario is built to teach and not to represent all real world problems.

For Monte Carlo models, which is best, a large number of iterations or averaging the results from a moderate number of iterations? Generally speaking, find the correct number of iterations by using the jack-knife technique to study errors in the final results:

- run two moderate size iterations and compare the results by looking at the differences in the calculated numbers,
- double the number of iterations until the errors appear fairly small, and
- then double the number of iterations for the final run.

Better results are often obtained by averaging iteration details which will smooth inconsistencies.

SUMMARY

Life-cycle costs include cradle to grave costs. When failure costs are included, the quantity of manpower required can be engineered which avoids the use of antique rules of thumb about how maintenance budgets are established.

LCC techniques provide methods to consider trade-off ideas with visualization techniques as described above which are helpful for engineers. Likewise LCC analysis provides NPV techniques of importance for financial organizations, and LCC details give both groups common ground for communication. With LCC details the financial organizations can complete DCF calculations.

Some chemical plants have cost values and failure data for ANSI pumps that are different than shown above—for example, coupling costs is ~US$100 and the associated logistics costs are ~US$75 for couplings with a MTBF of ~3 years, seal life is ~1.5 years, shaft life is ~4.5 years, impeller life is ~3.5 years, pump housing life is ~6 years, and the costs of bearings is ~US$140. Students are encouraged to use these figures to recalculate the values shown above as a training exercise to understand LCC methodology. Of course, these values for a chemical plant will result in higher maintenance costs and greater maintenance expenditures—the question of how much is left to the student to polish individual skills using the templates shown above.

Each of the examples described above can be made more accurate by using more complicated models. For one example, in the Monte Carlo model, the time for repairs can be changed from a fixed interval to a statistical interval by simply using a log-normal distribution and this will increase the amount of realism for time expended and costs incurred. Also spare part quantities can be calculated. Again the student is encouraged to try these techniques as skill builders.

Good alternatives for LCC require creative ideas. This is the role of the engineer to suggest and recommend cost effective alternatives. Much lower LCC are obtained when creative efforts are employed in the design area--making changes downstream in the operating plants has smaller chances for improvements because it’s employed too late in the improvement cycle. Design engineers are the most important link in devising cost effective plants and naturally the burden of LCC falls on their shoulders—but design engineers can’t perform an effective analysis unless they have reasonable failure data from operations. Thus the need for plant and industry databases of failure characteristics—remember, to obtain good failure data, both failure and success data must be identifies. If only the failure information is considered, then the failure database will be too pessimistic and no one will believe it and worse yet, no one will use overly pessimistic data.

LCC is simply a way-stop on the never ending journey for reducing costs. LCC is clearly not a destination. LCC provides the tools to engineer maintenance budgets and costs.

The authors welcome constructive comments and criticism regarding LCC information and associated techniques presented.

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