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Life Cycle Cost And Good Practices

by

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ABSTRACT

Life cycle costs (LCC) concepts are merged with installation and operating practices for a pumping system to form a reliability model. Reliability models show how inherent component life is reduced by various practices. As failed components are replaced, changes occur in the LCC values. The outcome of several installation/use alternatives and several grades of pumps are described in net present value format.

LIFE CYCLE COST INTRODUCTION

Life cycle costs are total costs from inception to disposal for both equipment and projects (Barringer 1996). Analytical studies and estimates of total costs are methods for finding life cycle costs. 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 is strongly influenced by equipment grade, installation/use practices, and maintenance practices. The issue: Make LCC understandable and usable by the average engineer as a working tool to "buy right rather than buying cheap".

LCC analysis helps engineers justify equipment and process selection based on total costs rather than initial purchase price. The sum of operation, maintenance, and disposal costs far exceed procurement costs. Life cycle costs are 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 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--a portion of the work effort involves applying art and science to practices of installation, maintenance and use of pumps.

Procurement costs are widely used as the primary (and sometimes only) criteria for equipment or system selection--i.e., cheap is good. Procurement cost is a simple criterion. It is easy to use. It often results in bad financial decisions! Procurement costs tell only one part of the story. The major cost lies in the care and feeding of equipment during its life. Simple procurement criteria often damages the financial well-being of the business enterprise as simple procurement cost is so cheap it's not affordable. Tools which only measure one thing usually give simple results which are 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”.

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 mid 1960's and 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 interests (Blanchard, 1990. 1992, 1995; Fabrycky 1991).

LCC emphasizes business issues by enhancing economic competitiveness to work for the lowest long-term cost of ownership. This requires engineers to worry about all cost details--they must 1) think like MBAs and 2) act like engineers for profit making enterprises.

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 financial ways.

Engineers usually identify obvious issues such a procurement cost, contract administration, installation cost, and other easily identifiable items. But here's the problem: 1) Engineers seldom get failure costs and routine operating costs correct, and 2) seldom do they quantify the effects of installation, operating, and maintenance practices on life costs. Engineers know in their hearts the effects of installation and use but they have difficulty quantifying and expressing the issues.

WHAT GOES INTO LIFE CYCLE COSTS?

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 1.

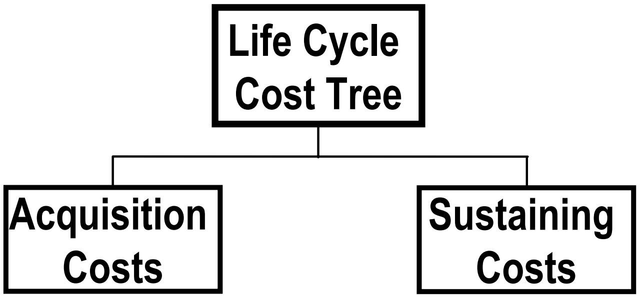


Figure 1: Top Levels Of Life Cycle Cost Tree

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.

In general, cost details for the acquisition tree shown in Figure 2, are usually identified and collected correctly. The collection of costs for the sustaining tree shown in Figure 3 is the major problem!

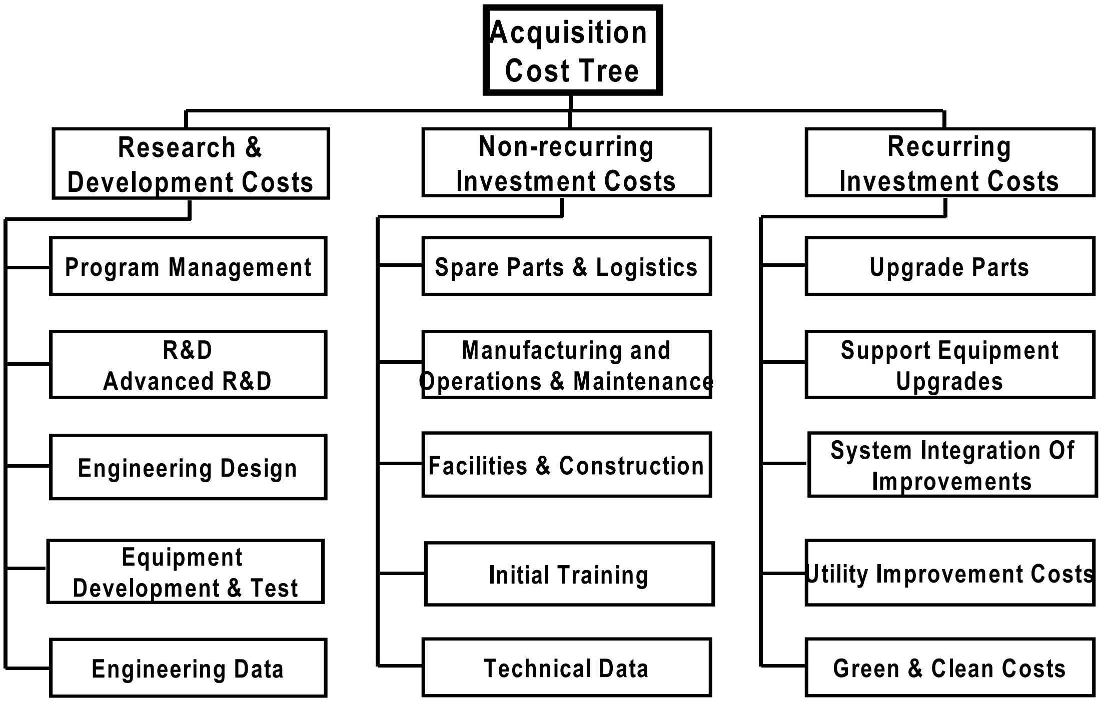


Figure 2: Acquisition Cost Tree

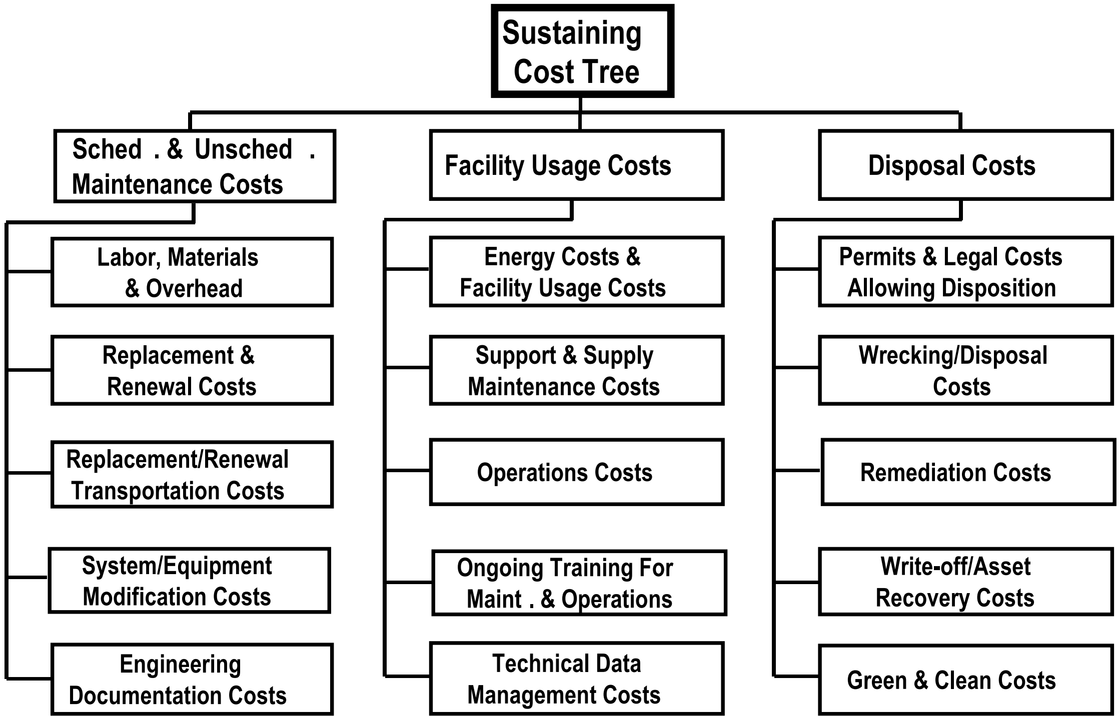


Figure 3: Sustaining Cost Tree

Frequently the cost of sustaining equipment is 2 to 20 times the acquisition cost. 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.

For the sustaining tree, the four items most difficult to collect are: 1) replacement/renewal costs, 2) replacement/renewal transportation costs, 3) support/supply maintenance costs, and 4) operating costs--particularly electrical costs because of varying loads on the equipment.

Most capital equipment authorizations ignore major portions of the sustaining cost tree as they lack sustaining funds expenditures--based on some "justifications": equipment never fails and surprisingly, some of the equipment never uses electricity!!. When failure costs are included, they appear as a percentage of the initial costs and are spread evenly through every year of the typical 20-year life for the project--for wear-out failure modes, the analysis is penalized by not including failures in the proper time span.

Complications arise in the sustaining tree which are driven by planned costs in the acquisition tree. About 65-75% of the total LCC is set when the equipment is specified--and most decisions are based on the acquisition tree which is the smallest portion of the LCC!!

LCC is a process for including appropriate costs as shown in Figure 4. Appropriateness changes with each specific case as shown (Fabryck 1991—Appendix A)

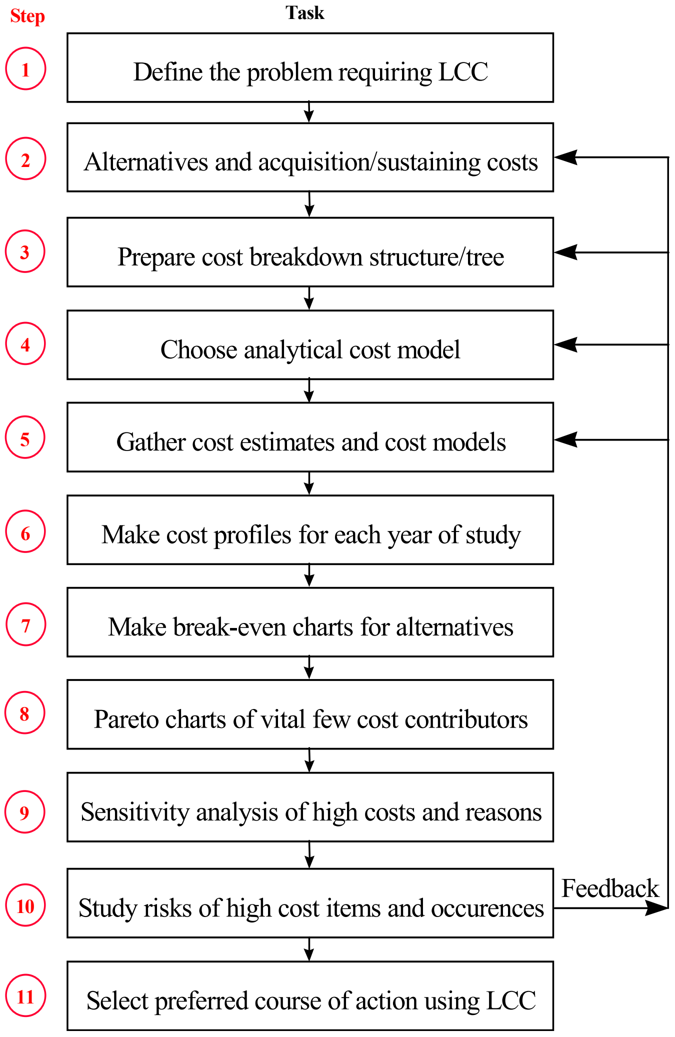


Figure 4: Process Flow For LCC Calculations

GRADE OF INSTALLATION AND GRADE OF EQUIPMENT

LCC accuracy improves and benefits from quantification of grade issues. Grade is a rank indication of the degree of refinement, features, or capabilities for installation and operation. The grade of equipment installation/use practices (and thus the costs) in the acquisition tree are precursors of failure costs covered in the sustaining tree.

Engineering drawings specify the grade of installation (and some times engineering specifies the grade of operation). Often the production department specifies the grade of operation. The grade of equipment installation and operation needs to priced-out as part of the specification process--it can't be ignored because if effects life cycle costs.

The maintenance department and operations department (if TPM oriented) specify the grade of maintenance.

Most engineers, during their career, are accused of gold plating, over-engineering, and wasting money on the grade of installation. Engineers are aware of how the installation grade strongly influences the number of failures for the sustaining tree, but they lack details for quantifying their opinions.

Much money rides on the correct decision of the grade of installation and the grade of operation, it must be carefully determined. Figure 5 provides facts for costing use. The resulting life multipliers alter the inherent reliability of equipment and change the base failure rates (low failure rates) to predicted failure rates (higher failure rates).

Fortunately, when LCC computations use details from Figure 5, engineers have facts to refute charges of gold plating, over design, high cost, and other overstatements or exaggerations from detractors.

Details for Figure 5 were obtained from the judgment and experience of many engineers about the effects of practices, costs of the practices, and effects of life by use of the practices. Details of Figure 5 quantify grade statements for LCC calculations

		Pump Curve % Off BEP	L/D Suction Straight Runs	Rotational Shaft Alignment	Piping Alignment	Rotational Balance	Foundation Design	Grouting
Best Practices	**Resulting Life Multiplier**	+ 5% to -10% of BEP	L/D = 10 to 12	±0.001 inches/inch error	±0.003 inch error	Smooth at 0.0198 ips	5 Times Equipment Mass	Monolithic And Adhesive Epoxy
Impeller	0.9726	98%	100%	100%	100%	100%	100%	100%
Housing	0.8547	86%	100%	100%	100%	100%	100%	100%
Pump Bearings	0.8719	98%	100%	100%	100%	99%	100%	100%
Seals	0.9533	98%	99%	100%	100%	100%	100%	100%
Shafts	0.8719	98%	100%	100%	100%	99%	100%	100%
Coupling	0.9801	99%	100%	99%	100%	100%	100%	100%
Motor Bearings	1.0000	100%	100%	100%	100%	100%	100%	100%
Motor Windings	1.0000	100%	100%	100%	100%	100%	100%	100%
Motor Rotor	1.0000	100%	100%	100%	100%	100%	100%	100%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%
Cost To Achieve Grade =		225%	130%	150%	150%	168%	400%	300%

		Pump Curve % Off BEP	L/D Suction Straight Runs	Rotational Shaft Alignment	Piping Alignment	Rotational Balance	Foundation Design	Grouting
Better Practices	**Resulting Life Multiplier**	+ 10% to -20% of BEP	L/D = 6 to 8	±0.003 inches/inch error	±0.010 inch error	Good at 0.0448 ips	3.5 Times Equipment Mass	Slightly Pourous But Adhesive
Impeller	0.6583	88%	95%	95%	94%	95%	95%	98%
Housing	0.5163	73%	95%	95%	92%	95%	95%	95%
Pump Bearings	0.3950	79%	90%	88%	88%	90%	90%	90%
Seals	0.4314	88%	90%	90%	84%	90%	90%	90%
Shafts	0.3950	79%	90%	88%	88%	90%	90%	90%
Coupling	0.5705	92%	95%	90%	94%	95%	90%	91%
Motor Bearings	0.6036	94%	93%	94%	97%	95%	90%	90%
Motor Windings	0.9776	100%	100%	100%	100%	100%	99%	99%
Motor Rotor	0.6036	94%	93%	94%	97%	95%	90%	90%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%
Cost To Achieve Grade =		181%	120%	120%	120%	138%	200%	200%

		Pump Curve % Off BEP	L/D Suction Straight Runs	Rotational Shaft Alignment	Piping Alignment	Rotational Balance	Foundation Design	Grouting
Good Practices	**Resulting Life Multiplier**	+15% to -30% of BEP	L/D = 1 to 3	±0.009 inches/inch error	±0.125 inches error	Rough at 0.248 ips	0.5 Times Equipment Mass or Stilt-Mounted	Cementitous & Low Adhesion
Impeller	0.1949	68%	75%	90%	69%	81%	88%	88%
Housing	0.1438	70%	80%	83%	64%	79%	78%	80%
Pump Bearings	0.0151	65%	60%	58%	40%	61%	50%	55%
Seals	0.0095	51%	60%	40%	40%	64%	55%	55%
Shafts	0.0151	65%	60%	58%	40%	61%	50%	55%
Coupling	0.1149	76%	80%	65%	71%	78%	70%	75%
Motor Bearings	0.0737	78%	80%	55%	80%	75%	60%	60%
Motor Windings	0.8625	97%	100%	100%	100%	95%	96%	98%
Motor Rotor	0.0737	78%	80%	55%	80%	75%	60%	60%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%
Cost To Achieve Grade =		100%	100%	100%	100%	100%	100%	100%

Figure 5: Centrifugal Pump Practices, Life, And Costs

Issues of quality and grade are frequently mixed in our language. Grade involves a process for ranking or sorting of products and features for a comparative sense for the degree of excellence. Quality provides a fitness for purpose sense relating to the ability of goods or services to satisfy a given need. For example, if a low-grade installation of high-grade equipment is specified, the compliance of features and characteristics must meet the given need based on a proper specification.

The fickleness of financial demands and the changing marketplace make resolution of LCC problems difficult when approached in terms of absolutes. The right solution today may be the wrong solution tomorrow. Based on our internal records, we have problems recasting the past, and we know predicting the future with assurance is difficult. This quandary requires the use of alternatives for justifications and the consideration of probabilities for occurrences of events.

Similarly, the maintenance grade must be properly specified and administered as all elements must bear on the ability of the equipment/installation/operation to satisfy a given need for minimizing the lowest long term cost of ownership as found by LCC. Every example has its own unique set of costs and problems to solve for minimizing LCC. Remember that minimizing LCC pushes-up NPV and creates wealth for stockholders. Finding LCC requires finding details for both acquisition and sustaining costs with many details--the most difficult analysis lies in the sustaining cost tree.

TRADE-OFF TOOLS FOR LCC

The effectiveness equation is a helpful tool for easing LCC calculations involving probabilities. It gives a figure-of-merit. It measures 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). Each element is a probability. The issue is finding a system effectiveness value, which gives lowest long-term cost of ownership with trade-off considerations:

System effectiveness = Effectiveness/LCC

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

Effectiveness = availability * reliability * maintainability * capability

Each element of the effectiveness equation must have a firm datum, which changes with name- plate ratings to obtain a true value that lies between 0 and 1. You need these measures to help sell LCC.

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:

A = (uptime)/(uptime + downtime)

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. As availability grows, the capacity for making money increases because the equipment is in-service a larger percent of time. Watch out for self-serving definitions of convenience not in the best interest of stockholders such as (uptime + downtime) < 8760 hours per year as the lack of making money is a LCC issue.

A few key words describing availability in quantitative words are: on-line time, stream factor time, and a host of local operating terms including a <u>minimum</u> value for operational availability. Availability for equipment is required even though the equipment is not in actual operation, the production departments wants it available at least a specified amount of time to complete their tasks.

When you know availability, it allows estimates of uptime for a given interval. Suppose an operation is desired to operate around the clock (total time in one year is 8760 hours) and it has an availability of 98%. The process uptime is 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 for the designated time interval) to produce effective results. Availability is NOT the same as reliability. Availability tells how time is used.

Reliability deals with reducing the frequency of failures over a time interval. Reliability 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 (a yardstick for reliability) 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, high reliability requires a long MTBF. 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 often occurs by reducing errors from people or improving processes/procedures and these changes can usually be made at small costs. Or reliability is improved by equipment, which increases capital cost. Reliability improvements bring expectations 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 quantifying reliability are: mean time to failure, mean time between failures, mean time between/before maintenance actions, mean time between/before repairs, mean life of units, failure rates, and the <u>maximum</u> number of failures in a specified time interval.

If you want high reliability, you must have long mean times between failure when compared to the mission time. The reliability for a mission time of one year with equipment having a 30-year mean time to failure gives a reliability of 96.72%. This says the probability of successfully completing the one-year time interval without failure is almost 97 chances out of 100 that the equipment will not fail during the one-year interval. This statement of reliability also says the probability for failure is 3.278% as (reliability + unreliability) = 1. High reliability (low chance for failures) and high maintainability (predictable maintenance times) tend toward highly effective systems. Reliability tells the probability for achieving a failure free interval.

Maintainability deals with duration of maintenance outages or *how long* it takes to complete (ease and speed) 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) 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 then sets maintenance procedures and determine the length of repair times.

A key maintainability figure of merit is the mean time to repair (MTTR) and a limit for the <u>maximum</u> 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

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

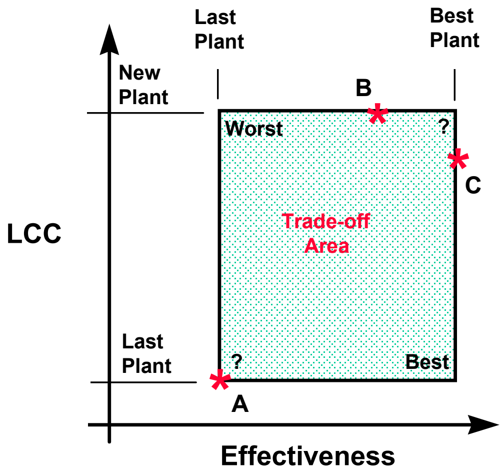
where μ is constant maintenance rate and MTTR is mean time to repair--the arithmetic average of repair time which is easier visualized than probability values. This simple, easy to use repair time criteria, is often expressed in exponential repair times rather than more accurate, but cumbersome, log-normal distributions of repair times which are skewed to the right by unusual and lengthy repairs. 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. When a limit of 24 hours is imposed, (99.9% of repairs will be accomplished in this time, or less), this 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 repair times) tend toward highly effective systems if capability is also maintained a high levels. Maintainability measures the probability of timely repairs.

Capability deals with productive output compared to inherent productive output. This index measures 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%. Capability measures *how well* the production activity is performed compared to the datum.

System effectiveness equations quantify important elements and associated costs 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 are helpful for understanding benchmarks, past, present, and future status as shown in Figure 6 for understanding trade-off information.

As engineers, we need graphics to provide a fundamental understanding to the problem. Figure 6 provides a graphical mechanism to display facts for effectiveness and life cycle costs. It helps explain details, and shows why certain actions are preferred. Each of us prefers selecting equipment or projects, which have low life cycle costs and high effectiveness--but often we do not accomplish this in real life because we cannot sell our ideas. Figure 6 is a presentation and sales tool using the system effectiveness elements described above.



Parameter	A Last Plant	B New Plant	C 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.

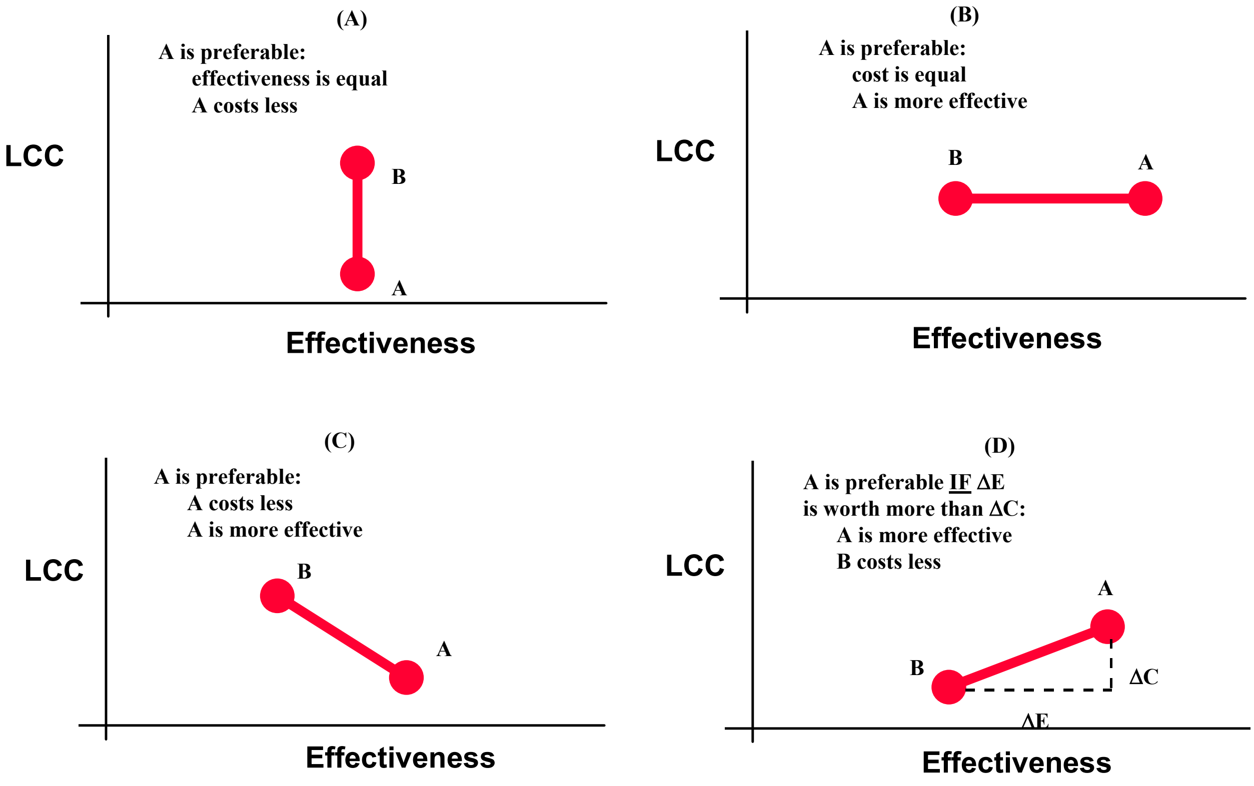


Figure 7: Some Possible Outcomes From Trade-Off Studies

System effectiveness equations have great impact on the LCC because so many decisions made in the early periods of a project carve LCC values into stone. About 2/3 of the total LCC are fixed during project conception (Followell 1995, Yates 1995). Expenditure of funds flows at a later time (Brennan 1985).

The chance to influence LCC cost reductions (Blanchard 1991) grows smaller when projects are converted into bricks and mortar as shown in Figure 8.

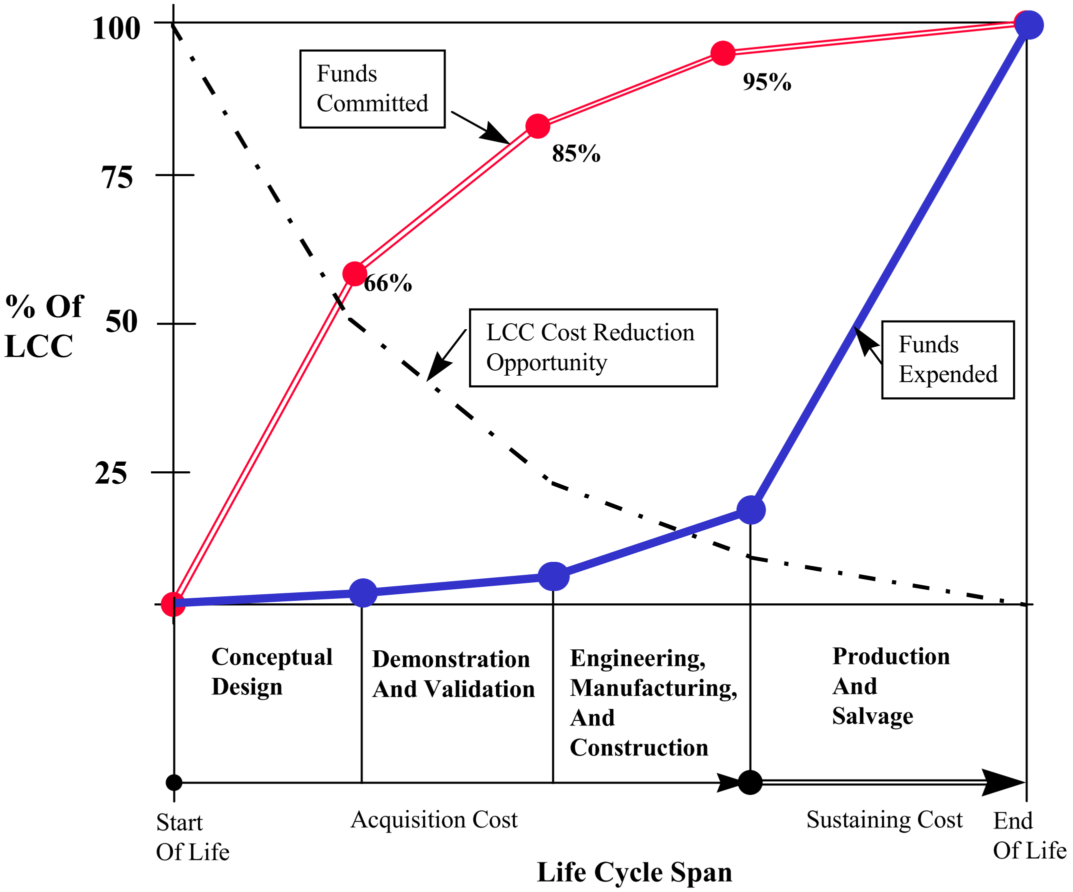


Figure 8: Funding Trends By Commitment And Expenditure

Calculate LCC early to influence final outcomes for better business results. Making major changes in LCC after projects are turned over to production is not possible because the die has been cast. LCC helps do the right thing upfront for projects. LCC must be sold--it's not always obvious. Seldom do we have enough money to do the project right, but we always have enough money to make mountains of repairs and grumble about the high cost of poorly configured plants.

LCC helps break poverty cycles of building cheap plants and repairing them often--at great expense. Argue for LCC methods as representing the stockholders interest--use facts for the details. Make decisions for LCC early in the life cycle span for maximum impact on the effort.

ENGINEERING FACTS

LCC requires facts driven by data. Most engineers say they lack data. However, 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 and grow to more complicated statistical analysis (Barringer 1995). Follow the guidelines for each step listed in Figure 4 to workout a typical engineering problem. Remember a single right or wrong method or 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 required for a new process, which operates continuously. When the pump fails (without an online spare), the process shuts down, and financial losses are incurred at US$5,000/hour of gross margin for the outage. Find an effective LCC alternative using a 20-year plant life.

The pump operates at moderate temperatures and pressures, and the environment is not particularly aggressive for corrosion. The pump consumes ~100 horsepower, with 85% efficiency at BEP at flow of 2,750 gallons per minute and a head of 121-feet. The pump size is 8-inch discharge, 10-inch suction, 14-inch case pumping fluids with a specific gravity =1. The motor has an efficiency of 95% using electrical power at a cost of US$165/yr-hp.

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

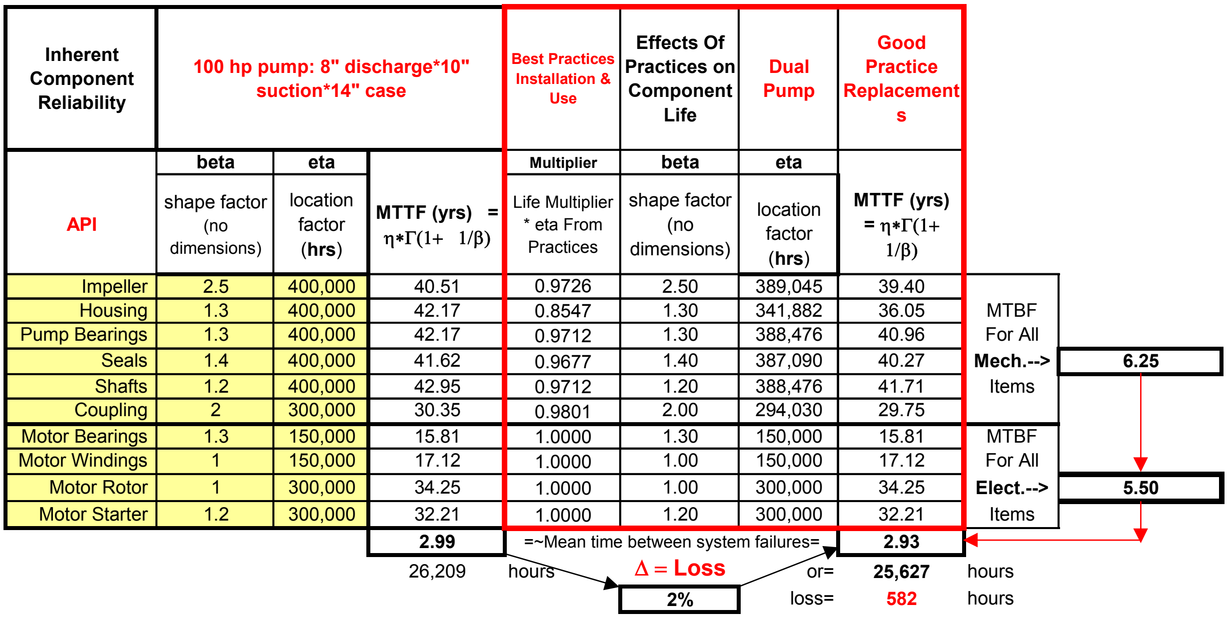
1. Do nothing is always the first alternative. This is not an attractive alternative for a new plant where a pump is mandatory. Therefore no effort is expended on this "should we?" issue.

2. Consider three pumps grades: ANSI, ANSI Enhanced, and API as shown in Figure 9--notice how higher grade pumps have increased life in the components. The inherent life of pump components is described using Weibull statistical formats (Abernethy 1998).

ANSI			ANSI Enhanced			API		
Inherent Component Reliability			**Inherent Component Reliability**			**Inherent Component Reliability**		
	beta	**eta**		**beta**	**eta**		**beta**	**eta**
ANSI	shape factor (no dimensions)	location factor (**hrs**)	**ANSI Enhanced**	shape factor (no dimensions)	location factor (**hrs**)	**API**	shape factor (no dimensions)	location factor (**hrs**)
Impeller	2.5	300,000	Impeller	2.5	300,000	Impeller	2.5	400,000
Housing	1.3	300,000	Housing	1.3	300,000	Housing	1.3	400,000
Pump Bearings	1.3	100,000	Pump Bearings	1.3	200,000	Pump Bearings	1.3	400,000
Seals	1.4	100,000	Seals	1.4	200,000	Seals	1.4	400,000
Shafts	1.2	300,000	Shafts	1.2	300,000	Shafts	1.2	400,000
Coupling	2	100,000	Coupling	2	100,000	Coupling	2	300,000
Motor Bearings	1.3	150,000	Motor Bearings	1.3	150,000	Motor Bearings	1.3	150,000
Motor Windings	1	150,000	Motor Windings	1	150,000	Motor Windings	1	150,000
Motor Rotor	1	300,000	Motor Rotor	1	300,000	Motor Rotor	1	300,000
Motor Starter	1.2	300,000	Motor Starter	1.2	300,000	Motor Starter	1.2	300,000

Figure 9: Inherent Life Of Pump Components

For Weibull statistics of components, the beta shape factor infers the failure mode, i.e., β < 1 is infant mortality, β = 1 is chance failure, and β > 1 is wear-out failure. The location parameter eta, η, describes the characteristic age at failure. Life multipliers from Figure 5 apply to the eta values thus decreasing the inherent life (the theoretical capability in a laboratory environment) to obtain the expected or predicted life shown for one case in Figure 10. The degraded Weibull factors in Figure 10 are used for calculating the birth and death of replacement parts by Monte Carlo simulations using an Excel spreadsheet.

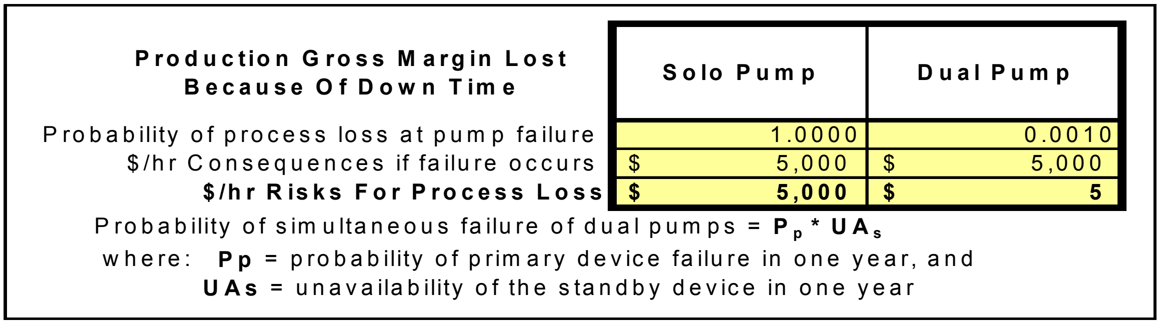


Inherent Component Reliability	100 hp pump: 8" discharge*10" suction*14" case			Best Practices Installation & Use	Effects Of Practices on Component Life	Dual Pump	Good Practice Replacements		
API	beta shape factor (no dimensions)	eta location factor (hrs)	MTTF (yrs) = $\eta*\Gamma(1+1/\beta)$	Multiplier Life Multiplier * eta From Practices	beta shape factor (no dimensions)	eta location factor (hrs)	MTTF (yrs) = $\eta*\Gamma(1+1/\beta)$		
Impeller	2.5	400,000	40.51	0.9726	2.50	389,045	39.40		
Housing	1.3	400,000	42.17	0.8547	1.30	341,882	36.05	MTBF	
Pump Bearings	1.3	400,000	42.17	0.9712	1.30	388,476	40.96	For All	
Seals	1.4	400,000	41.62	0.9677	1.40	387,090	40.27	Mech.-->	6.25
Shafts	1.2	400,000	42.95	0.9712	1.20	388,476	41.71	Items	
Coupling	2	300,000	30.35	0.9801	2.00	294,030	29.75		
Motor Bearings	1.3	150,000	15.81	1.0000	1.30	150,000	15.81	MTBF	
Motor Windings	1	150,000	17.12	1.0000	1.00	150,000	17.12	For All	
Motor Rotor	1	300,000	34.25	1.0000	1.00	300,000	34.25	Elect.-->	5.50
Motor Starter	1.2	300,000	32.21	1.0000	1.20	300,000	32.21	Items	
			2.99	=~Mean time between system failures=			2.93		
			26,209	hours	Δ = Loss	or=	25,627	hours	
					2%	loss=	582	hours	

Figure 10: Inherent Life Altered By Installation/Use Practices

Weibull characteristic values for the inherent reliability can be obtained from the manufacturer of the equipment, handbooks, websites, or scaled from operating experience. Notice how seemingly long individual lives of components in Figure 10 produce short life for the assembly when converted into a reliability model with effects of the installation and use practices for one grade of equipment. Also note the taxonomy of the system as it is broken into three parts for 1) mechanical components, 2) electrical system, and 3) the overall system---knowing the taxonomy is important for benchmarking purposes so that everyone describes the system with the same facts.

3. Two configurations will be considered: spared and no spare. Based on the cost for an outage, the following table calculates the process failure costs per hour for equipment outage:



Production Gross Margin Lost Because Of Down Time	Solo Pump	Dual Pump
Probability of process loss at pump failure	1.0000	0.0010
$/hr Consequences if failure occurs	$ 5,000	$ 5,000
$/hr Risks For Process Loss	**$ 5,000**	**$ 5**

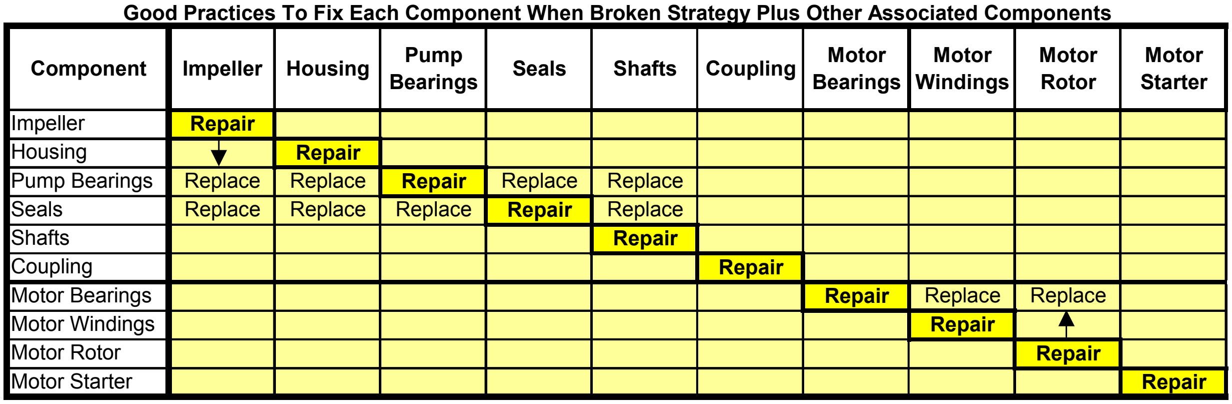
Probability of simultaneous failure of dual pumps = $P_p * UA_s$

where: Pp = probability of primary device failure in one year, and

UAs = unavailability of the standby device in one year

Figure 11: Consequence Of Failures

4. Two maintenance strategies are evaluated: fix when broken (no explanation needed), and good maintenance practices where designated unfailed parts in the equipment are replaced when the equipment is open for repair of failed units. For example, Figure 11 says that when an impeller fails and is replaced, that pump bearings and seals are also replaced, and so forth. When corollary items are replaced, remaining life in the component is wasted at the expense of reducing future early time pending failures. Good maintenance practices improve reliability by increasing mean times between failure with only minor increases in costs.



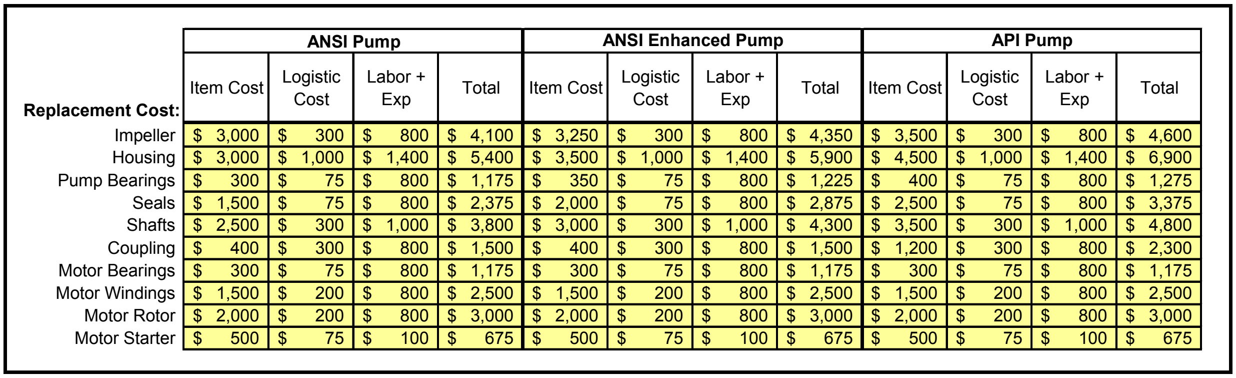
Good Practices To Fix Each Component When Broken Strategy Plus Other Associated Components

Component	Impeller	Housing	Pump Bearings	Seals	Shafts	Coupling	Motor Bearings	Motor Windings	Motor Rotor	Motor Starter
Impeller	**Repair**									
Housing	↓	**Repair**								
Pump Bearings	Replace	Replace	**Repair**	Replace	Replace					
Seals	Replace	Replace	Replace	**Repair**	Replace					
Shafts					**Repair**					
Coupling						**Repair**				
Motor Bearings							**Repair**	Replace	Replace	
Motor Windings								**Repair**	↑	
Motor Rotor									**Repair**	
Motor Starter										**Repair**

Figure 12: Good Maintenance Practices

5. The cost of maintenance failures carries labor and component costs. Whereas unfailed replacement parts are installed with little or no increase in the labor hours, only an increase in the cost for the replacement parts incurred as a portion of the good maintenance practices. Every company has a different cost structure determine by volume, partnership agreements, and other commercial issues that are known to insiders but are difficult to determine by individuals outside of companies. Notice in most cases that costs in Figure 13 are rounded to the nearest $100. Don't strain at the gnats to get too many significant figures--it's not worth the effort.

6. Acquisition cost by equipment grade and by grade of installation has major impact on LCC as upfront costs. Figure 14 shows the prices for each category. At the point of specification and procurement, many people believe the "extras" for grade enhancement are not reasonable or affordable.



	ANSI Pump				ANSI Enhanced Pump				API Pump			
Replacement Cost:	Item Cost	Logistic Cost	Labor + Exp	Total	Item Cost	Logistic Cost	Labor + Exp	Total	Item Cost	Logistic Cost	Labor + Exp	Total
Impeller	$ 3,000	$ 300	$ 800	$ 4,100	$ 3,250	$ 300	$ 800	$ 4,350	$ 3,500	$ 300	$ 800	$ 4,600
Housing	$ 3,000	$ 1,000	$ 1,400	$ 5,400	$ 3,500	$ 1,000	$ 1,400	$ 5,900	$ 4,500	$ 1,000	$ 1,400	$ 6,900
Pump Bearings	$ 300	$ 75	$ 800	$ 1,175	$ 350	$ 75	$ 800	$ 1,225	$ 400	$ 75	$ 800	$ 1,275
Seals	$ 1,500	$ 75	$ 800	$ 2,375	$ 2,000	$ 75	$ 800	$ 2,875	$ 2,500	$ 75	$ 800	$ 3,375
Shafts	$ 2,500	$ 300	$ 1,000	$ 3,800	$ 3,000	$ 300	$ 1,000	$ 4,300	$ 3,500	$ 300	$ 1,000	$ 4,800
Coupling	$ 400	$ 300	$ 800	$ 1,500	$ 400	$ 300	$ 800	$ 1,500	$ 1,200	$ 300	$ 800	$ 2,300
Motor Bearings	$ 300	$ 75	$ 800	$ 1,175	$ 300	$ 75	$ 800	$ 1,175	$ 300	$ 75	$ 800	$ 1,175
Motor Windings	$ 1,500	$ 200	$ 800	$ 2,500	$ 1,500	$ 200	$ 800	$ 2,500	$ 1,500	$ 200	$ 800	$ 2,500
Motor Rotor	$ 2,000	$ 200	$ 800	$ 3,000	$ 2,000	$ 200	$ 800	$ 3,000	$ 2,000	$ 200	$ 800	$ 3,000
Motor Starter	$ 500	$ 75	$ 100	$ 675	$ 500	$ 75	$ 100	$ 675	$ 500	$ 75	$ 100	$ 675

Figure 13: Component Replacement Costs

Of course the answer for grade enhancements is found by calculating the effects on life and replacement costs. Notice the price of foundations is driven by the weight of the system and mass required by the grade of installation. Similar relationships exist for other components in the system and the grade of installation noted in Figure 5.

Concrete foundation price ($/yd) installed	$ 500
ANSI Pump & Motor Weight (lbs)	7500

	ANSI					ANSI Enhanced					API		
	Good Practices Installation & Use	**Better Practices Installation & Use**	**Best Practices Installation & Use**	ANSI **+** Pump & Motor Wt (lbs)	8000	**Good Practices Installation & Use**	**Better Practices Installation & Use**	**Best Practices Installation & Use**	API Pump & Motor Wt (lbs)	10000	**Good Practices Installation & Use**	**Better Practices Installation & Use**	**Best Practices Installation & Use**
Purchase Price	$ 5,000	$ 5,000	$ 5,000			$ 7,000	$ 7,000	$ 7,000			$ 20,000	$ 20,000	$ 20,000
Factory balance	$ 100	$ 137	$ 167			$ 125	$ 171	$ 209			$ 200	$ 274	$ 334
Field align rotating components	$ 150	$ 180	$ 225			$ 175	$ 210	$ 263			$ 300	$ 360	$ 450
Foundations	$ 482	$ 3,376	$ 4,823			$ 514	$ 3,601	$ 5,144			$ 643	$ 4,501	$ 6,430
Mount pump to foundation	$ 400	$ 600	$ 800			$ 500	$ 700	$ 1,000			$ 600	$ 800	$ 1,200
Grout	$ 250	$ 500	$ 750			$ 250	$ 500	$ 750			$ 250	$ 500	$ 750
Valves/fittings	$ 1,000	$ 1,000	$ 1,000			$ 1,000	$ 1,000	$ 1,000			$ 1,000	$ 1,000	$ 1,000
Straight run of pipe	$ 100	$ 120	$ 130			$ 100	$ 120	$ 130			$ 100	$ 120	$ 130
Assembly of piping system	$ 1,000	$ 1,200	$ 1,500			$ 1,000	$ 1,200	$ 1,500			$ 1,000	$ 1,200	$ 1,500
Field align piping systems	$ 1,000	$ 1,200	$ 1,500			$ 1,000	$ 1,200	$ 1,500			$ 1,000	$ 1,200	$ 1,500
Electrical	$ 15,000	$ 15,000	$ 15,000			$ 15,000	$ 15,000	$ 15,000			$ 15,000	$ 15,000	$ 15,000
Instrumentation	$ 500	$ 500	$ 500			$ 500	$ 500	$ 500			$ 500	$ 500	$ 500
Modify Impeller For BEP	$ -	$ 1,000	$ 2,250			$ -	$ 1,000	$ 2,250			$ -	$ 1,000	$ 2,250
95% efficiency motor	$ 10,000	$ 10,000	$ 10,000			$ 10,000	$ 10,000	$ 10,000			$ 10,000	$ 10,000	$ 10,000
Total =	$ 34,982	$ 39,813	$ 43,645		Total =	$ 37,164	$ 42,202	$ 46,245		Total =	$ 50,593	$ 56,455	$ 61,044

Figure 14: Capital Acquisition And Installation Costs

7. Operational details for the pump are shown in Figure 15. These elements are required for power consumption. Operating conditions will vary randomly with time as limited by conditions. The cost of electricity for large pumps is usually the most expensive sustaining cost item.

Energy Costs & Pump Details:	**Good Practices**	**Better Practices**	**Best Practices**
Practice allows flow of BEP -x%	-30%	-20%	-10%
Practice plans for aimpoint flow of % BEP	100%	100%	100%
Practice allows flow of BEP +x%	15%	10%	5%
Efficiency at lowest allowed flow	77%	81%	83%
Efficiency at BEP	85%	85%	85%
Efficiency at highest allowed flow	82%	83%	84%
Lowest allowed flow (gpm)	1,925	2,200	2,475
Flow at BEP (gpm)	2,750	2,750	2,750
Highest allowed flow (gpm)	3,162	3,025	2,885
Total head at lowest allowed flow (ft)	139	134	128
Total head at BEP (ft)	121	121	121
Total head at highest allowed flow (ft)	108	112	116
Specific gravity of fluid	1	1	1
Horsepower for lowest allowed flow (hp)	88	92	96
Horsepower for BEP (hp)	99	99	99
Horsepower for highest allowed flow (hp)	105	103	101
Motor Horsepower Required: Flow*Head*SpG	99	99	99
Motor Efficiency	95%	95%	95%
Electrical cost $/(yr-hp)	165	165	165
Electrical costs per year @ installed hp ($/yr)	$ 17,170	$ 17,170	$ 17,170

Figure 15: Pumping Cost And Performance Details

8. The acquisition cost tree for Figure 2 needs a host of other details for the LCC calculation such as program management cost down through the environmental issues of cleaning the site at the end of the project and renewing the site to it's green-field environment. Typically these costs are identified in most projects and well described as an acquisition cost by most companies. For this example, assume program management, engineering design, and engineering data costs are $5000 for the R&D leg of Figure 2. For the non-recurring costs of Figure 2, plan for no spare parts, no additional manufacturing/operations/Maintenance or facilities/construction costs except as defined in Figure 14, and allow initial training costs plus technical data costs to occur in year 1 for $5000. For the recurring cost of Figure 2, assume no costs will be incurred.

9. The sustaining cost tree of Figure 3 is supported by the details described in Figures 5 and 9 to drive the birth/death of replacement parts by means of the effects of practices as described in Figure 10. The consequences of failures are described in Figure 11, and the maintenance practices of Figure 12 will alter the number of parts required. Figure 13 gives prices for the replacement parts while figure 15 describes the consumption of electrical power. The disposal costs for year 20 of the project would be $5000.

Step 3: Prepare cost breakdown structure/tree.

Each case for the cost breakdown structure will incur cost in these categories:

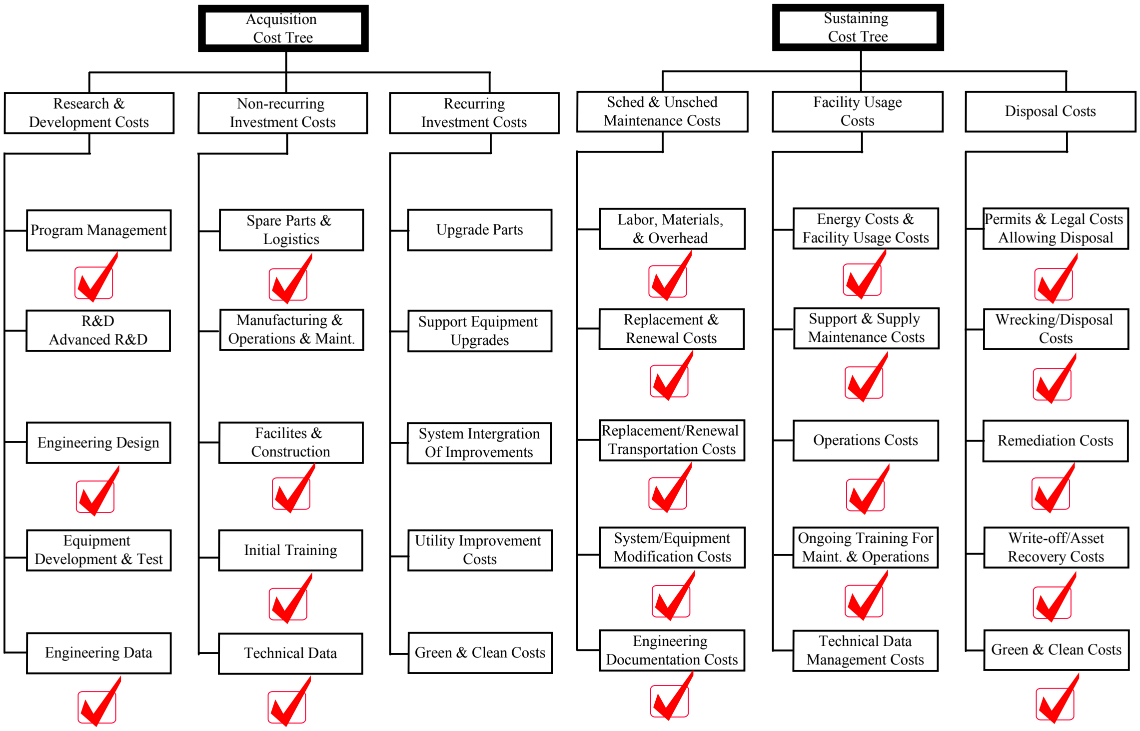


Figure 16: Cost Components For Each Grade Of Pump

Step 4: Choose analytical cost model.

The cost model is an engineering spreadsheet for calculating net present value (NPV) using a discount rate of 12%. The spreadsheet merges cost details and failure details to prepare the NPV calculations. Failure costs are incurred by each year as they fail using a Monte Carlo simulation of birth/death to cover the uncertainty. The simulation is performed using an Excel spreadsheet.

The simple case of using a constant failure rate for each component makes the calculation of maintenance cost easy, for a first cut. However, constant failure rates do not produce accurate results because the NPV calculation is sensitive to what year the failures occur; and this in turn drives costs as delayed costs have big advantages but constant failure rates dismiss this advantage.

For the purpose of this paper only, the cost items identified above in step 2, item 8 are not included so that only the direct acquisition costs and direct sustaining costs are included to provide an unadulterated calculation of NPV. Remember, you would not ignore this issue for a AFE submission.

Step 5: Gather cost estimates and cost models.

This is the complicated section where all the details are assembled.

Alternative #1-ANSI Pump: Use the following details—

Start with the inherent life for the ANSI pump from Figure 9. Alter the life by the factors in Figure 5 for three different installation/use practices.

Allow installation of a solo pump or a dual pump with the consequences of failure costs as described in Figure 11.

Use two maintenance practices of fix when broken or good maintenance practices as described in Figure 12.

Draw maintenance costs from Figure 13 for the ANSI pump. Use capital costs from Figure 14 for the ANSI pump.

Use power consumption costs from Figure 15 allowing random variation in the costs depending upon the practices employed. Add the acquisition/sustaining costs from Step 3's items 8 and 9.

This requires six models (six NPV values) for the ANSI case for the solo pump case plus six models for the dual pump case for a total of 12 models and produces 12 NPV values. Because only costs are considered, the NPV with the least costs will be considered the initial winner.

NPV's along with the product of availability and reliability (as a limited subset of the effectiveness equation) will be used for the tradeoff calculations.

Alternative #2-ANSI Enhanced Pump: Use the following details—

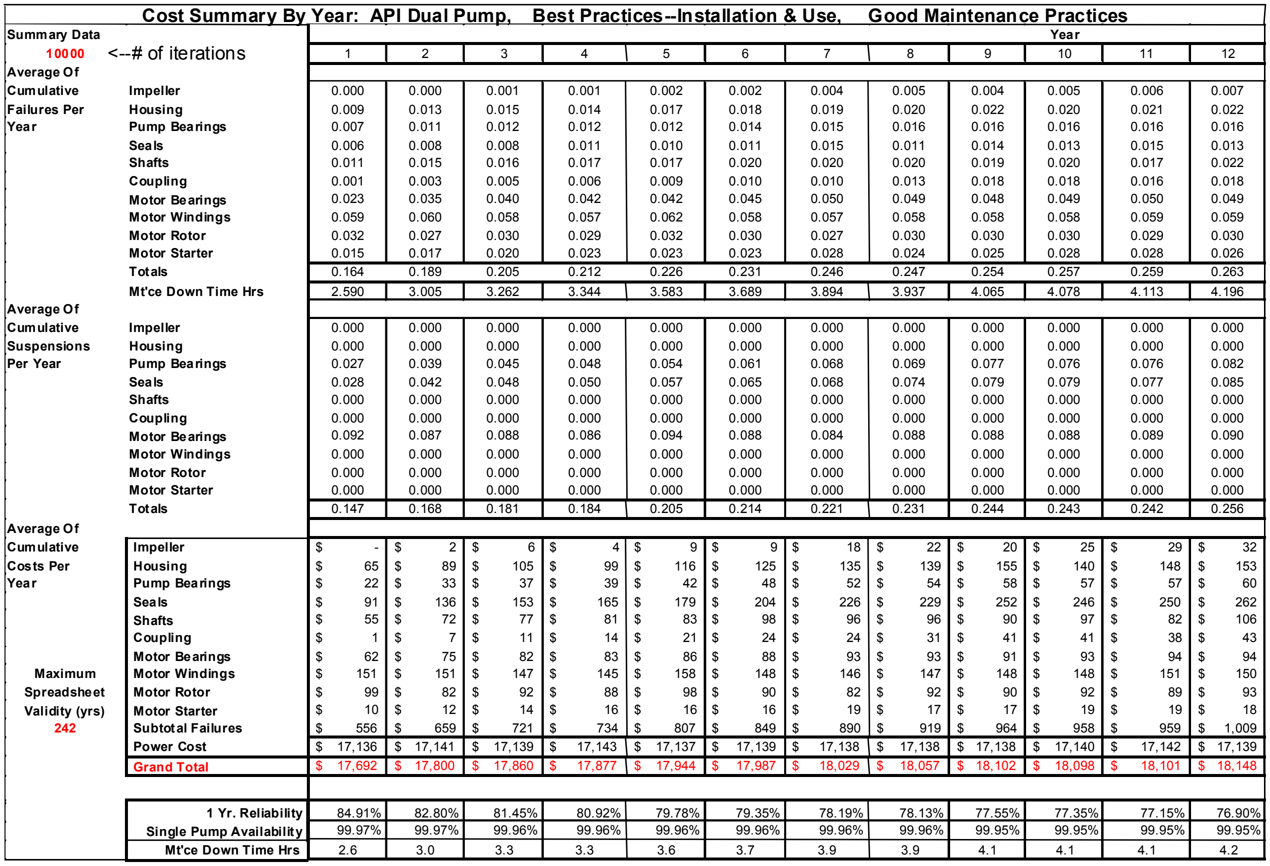
Same as for alternative #1 but using ANSI enhanced details.

Alternative #3-API Pump: Use the following details—

Same as for alternative #1 but using ANSI enhanced details.

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

This step will take into account the annualized charges shown plus the lumped charges at the front and rear end of the project. Figure 17 shows spreadsheet details of the Monte Carlo simulation by year for a portion of the 20 year study cycle. Each iteration is a 20 year "snapshot" of the birth and death of components and many iterations are required for obtaining a consistent result. Figure 17 also shows the suspended component usage for unfailed items replaced as part of good maintenance practices. Notice how maintenance hours required for the equipment grow with time, and since failures are increasing, reliability declines.



Cost Summary By Year: API Dual Pump, Best Practices--Installation & Use, Good Maintenance Practices

Summary Data		Year											
10000	<--# of iterations	1	2	3	4	5	6	7	8	9	10	11	12
Average Of													
Cumulative	Impeller	0.000	0.000	0.001	0.001	0.002	0.002	0.004	0.005	0.004	0.005	0.006	0.007
Failures Per	Housing	0.009	0.013	0.015	0.014	0.017	0.018	0.019	0.020	0.022	0.020	0.021	0.022
Year	Pump Bearings	0.007	0.011	0.012	0.012	0.012	0.014	0.015	0.016	0.016	0.016	0.016	0.016
	Seals	0.006	0.008	0.008	0.011	0.010	0.011	0.015	0.011	0.014	0.013	0.015	0.013
	Shafts	0.011	0.015	0.016	0.017	0.017	0.020	0.020	0.020	0.019	0.020	0.017	0.022
	Coupling	0.001	0.003	0.005	0.006	0.009	0.010	0.010	0.013	0.018	0.018	0.016	0.018
	Motor Bearings	0.023	0.035	0.040	0.042	0.042	0.045	0.050	0.049	0.048	0.049	0.050	0.049
	Motor Windings	0.059	0.060	0.058	0.057	0.062	0.058	0.057	0.058	0.058	0.058	0.059	0.059
	Motor Rotor	0.032	0.027	0.030	0.029	0.032	0.030	0.027	0.030	0.030	0.030	0.029	0.030
	Motor Starter	0.015	0.017	0.020	0.023	0.023	0.023	0.028	0.024	0.025	0.028	0.028	0.026
	Totals	0.164	0.189	0.205	0.212	0.226	0.231	0.246	0.247	0.254	0.257	0.259	0.263
	Mt'ce Down Time Hrs	2.590	3.005	3.262	3.344	3.583	3.689	3.894	3.937	4.065	4.078	4.113	4.196
Average Of													
Cumulative	Impeller	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Suspensions	Housing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Per Year	Pump Bearings	0.027	0.039	0.045	0.048	0.054	0.061	0.068	0.069	0.077	0.076	0.076	0.082
	Seals	0.028	0.042	0.048	0.050	0.057	0.065	0.068	0.074	0.079	0.079	0.077	0.085
	Shafts	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Coupling	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Motor Bearings	0.092	0.087	0.088	0.086	0.094	0.088	0.084	0.088	0.088	0.088	0.089	0.090
	Motor Windings	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Motor Rotor	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Motor Starter	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Totals	0.147	0.168	0.181	0.184	0.205	0.214	0.221	0.231	0.244	0.243	0.242	0.256
Average Of													
Cumulative	Impeller	$ -	$ 2	$ 6	$ 4	$ 9	$ 9	$ 18	$ 22	$ 20	$ 25	$ 29	$ 32
Costs Per	Housing	$ 65	$ 89	$ 105	$ 99	$ 116	$ 125	$ 135	$ 139	$ 155	$ 140	$ 148	$ 153
Year	Pump Bearings	$ 22	$ 33	$ 37	$ 39	$ 42	$ 48	$ 52	$ 54	$ 58	$ 57	$ 57	$ 60
	Seals	$ 91	$ 136	$ 153	$ 165	$ 179	$ 204	$ 226	$ 229	$ 252	$ 246	$ 250	$ 262
	Shafts	$ 55	$ 72	$ 77	$ 81	$ 83	$ 98	$ 96	$ 96	$ 90	$ 97	$ 82	$ 106
	Coupling	$ 1	$ 7	$ 11	$ 14	$ 21	$ 24	$ 24	$ 31	$ 41	$ 41	$ 38	$ 43
	Motor Bearings	$ 62	$ 75	$ 82	$ 83	$ 86	$ 88	$ 93	$ 93	$ 91	$ 93	$ 94	$ 94
Maximum	Motor Windings	$ 151	$ 151	$ 147	$ 145	$ 158	$ 148	$ 146	$ 147	$ 148	$ 148	$ 151	$ 150
Spreadsheet	Motor Rotor	$ 99	$ 82	$ 92	$ 88	$ 98	$ 90	$ 82	$ 92	$ 90	$ 92	$ 89	$ 93
Validity (yrs)	Motor Starter	$ 10	$ 12	$ 14	$ 16	$ 16	$ 16	$ 19	$ 17	$ 17	$ 19	$ 19	$ 18
242	Subtotal Failures	$ 556	$ 659	$ 721	$ 734	$ 807	$ 849	$ 890	$ 919	$ 964	$ 958	$ 959	$ 1,009
	Power Cost	$ 17,136	$ 17,141	$ 17,139	$ 17,143	$ 17,137	$ 17,139	$ 17,138	$ 17,138	$ 17,138	$ 17,140	$ 17,142	$ 17,139
	Grand Total	$ 17,692	$ 17,800	$ 17,860	$ 17,877	$ 17,944	$ 17,987	$ 18,029	$ 18,057	$ 18,102	$ 18,098	$ 18,101	$ 18,148
	1 Yr. Reliability	84.91%	82.80%	81.45%	80.92%	79.78%	79.35%	78.19%	78.13%	77.55%	77.35%	77.15%	76.90%
	Single Pump Availability	99.97%	99.97%	99.96%	99.96%	99.96%	99.96%	99.96%	99.96%	99.95%	99.95%	99.95%	99.95%
	Mt'ce Down Time Hrs	2.6	3.0	3.3	3.3	3.6	3.7	3.9	3.9	4.1	4.1	4.1	4.2

Figure 17: Results Of Monte Carlo Simulation

The grand total of costs in Figure 17 is replicated five times and averaged to reduce the errors that randomly occur. The averaged costs for each period go into the net present value calculation. Figure 17 shows that power costs are 97% of total cost in the early years and decline to 94% as maintenance costs increase with time for the condition explained in the spreadsheet heading. Of course the ratio of (electrical costs)/(total annual costs) are substantially different for lower grade equipment, lower grade installation/use and solo pumps. Figure 17 is shown only for the first 12 months so the spreadsheet figures are visible when reproduced.

Since the pump in Figure 17 is a dual pump and the availability is reported for a single unit, the system availability must be calculated. Two pumps in parallel with 99.95% availability and short repair times as observed in Figure 17 is: ≈1-(1-0.9995)^2 ≈ 0.999,999,8. In short, the dual pumping system is highly available.

The probability of system failure in Figure 11 can be found from Figure 17 (using just the numbers shown in the figure). Probability of failure in one year is 1-76.90% = 0.231, and the unavailability is 1-99.95% = 0.0005. Probability of simultaneous failure = 0.231*0.0005 = 0.0001 thus the consequences of failure shown in Figure 11 are too harsh at a penalty at $5/hour of downtime for this case--but this is a trivial matter.

Each case described above in step 5 produces a cost profile by means of Monte Carlo simulation. Results of the cost profiles are converted into net present values as summarized below in Figure 18 along with availability and reliability values which approximate the effectiveness equation--assuming that maintainability and capability are approximately the same for each pump.

The lower grade "good" installations have many failurs which increases NPB. The effectiveness values reported in Figure 18 are ~0% because of the low reliability values. Remember the most favorable NPV values in Figure 18 for this case are those with the *smallest negative values*.

Summary Of Net Present Values & ~Effectiveness

	Good Maintenance			Fix When Broken		
	Installation/Use Practices			Installation/Use Practices		
	Good	Better	Best	Good	Better	Best
ANSI						
Solo NPV	-$2,684,838	-$277,688	**-$197,328**	-$3,771,088	-$292,286	**-$201,700**
Solo R*A	~0%	43%	65%	~0%	38%	61%
Dual NPV	-$340,851	-$125,753	**-$121,634**	-$205,528	-$122,566	**-$120,078**
Dual R*A	~0%	43%	65%	~0%	38%	61%
ANSI +						
Solo NPV	-$2,267,845	-$246,576	**-$185,964**	-$1,987,263	-$253,709	**-$187,836**
Solo R*A	~0%	51%	70%	~0%	48%	68%
Dual NPV	-$310,021	-$126,696	**$124,681**	-$251,370	-$123,250	**$121,803**
Dual R*A	~0%	52%	70%	~0%	48%	68%
API						
Solo NPV	-$1,487,132	-$211,437	**-$177,185**	-$1,466,641	-$213,621	**-$177,869**
Solo R*A	~0%	65%	78%	~0%	63%	77%
Dual NPV	-$258,181	-$135,543	**-$133,564**	-$225,720	**-$133,286**	-$134,669
Dual R*A	~0%	65%	78%	~0%	63%	77%

Figure 18: Net Present Value Summary

If cost is the only consideration and effectiveness (~R*A) has no value to the end user, then choose ANSI dual equipment, best installation grade, and fix when broken maintenance practices as the best NPV at -$120,078 with ~R*A= 61%. This is simply an accounting position without regard for other trade-off features. The top ten alternatives from Figure 18 are shown in Figure 19.

Top Ten Alternatives

Alternative	Pump	Dual/Solo	Install/Use Practice	Maintenance Strategy	NPV	Effect. ~ R*A	Δ % For NPV	Δ % For ~R*A
1	ANSI	Dual	Best	Fix When Broken	-$120,078	61%	--	--
2	ANSI	Dual	Best	Good Replacements	-$121,634	65%	1%	7%
3	ANSI+	Dual	Best	Fix When Broken	-$121,803	68%	1%	11%
4	ANSI	Dual	Better	Fix When Broken	-$122,566	38%	2%	-38%
5	ANSI+	Dual	Better	Fix When Broken	-$123,250	48%	3%	-21%
6	ANSI+	Dual	Best	Good Replacements	-$124,681	70%	4%	15%
7	ANSI	Dual	Better	Good Replacements	-$125,753	43%	5%	-30%
8	ANSI+	Dual	Better	Good Replacements	-$126,696	52%	6%	-15%
9	API	Dual	Better	Fix When Broken	-$133,286	63%	11%	3%
10	API	Dual	Best	Good Replacements	-$133,564	78%	11%	28%

Figure 19: Top Ten Alternatives--Rank Order

If you are a maintenance engineer, **rewarded for fighting fires**, then you will agree with the accounting decision for alternative 1 in Figure 19. Lower reliability values pace the simplified effectiveness numbers will provide more opportunities to "show your stuff" for repairs.

If you are reliability engineer, **rewarded for avoiding problems**, then you may select alternative 6 from Figure 19 as having modest cost increases (+4% in NPV) but substantial improvements in effectiveness (+15%). Or, perhaps you will argue for other alternatives having some increases in NPV but greater increases in effectiveness than the base case of alternative 1.

Figure 19 shows alternatives 4, 5, 7, and 8 are poor choices. Costs are higher and effectiveness are lower than the base case of alternative 1 making them unworthy of further considerations. Also note that Figure 19 does not include two general categories for the top 10 list: 1) solo pumps and 2 low grades for installation/use. Solo pumps incur large gross margin loses when pump components fail thus a solo pump is a poor choice for all grades of pumps and all grades of installation and use. In general the poorer grades of installation/use (i.e., good) are high cost alternatives.

Be careful of generalizing Figure 19 that all API pumps are "bad buys"--conditions such as hgih temperature, etc. for API equipment were not a requirement. Thus API pumps were ranked less favorable in the list of NPV alternatives because their strong features are not required for this case.

Step 7: Make break-even charts for alternatives.

Breakeven charts are useful tools for showing a quick grasp of details. The fix when broken (FWB) strategy is slightly less expensive than the good maintenance (GM) practice as shown in Figure 19. FWB results in more failures but life is not wasted in replacing parts that have not yet failed. Thus lower cost is obtained by a sacrifice in reliability for the system.

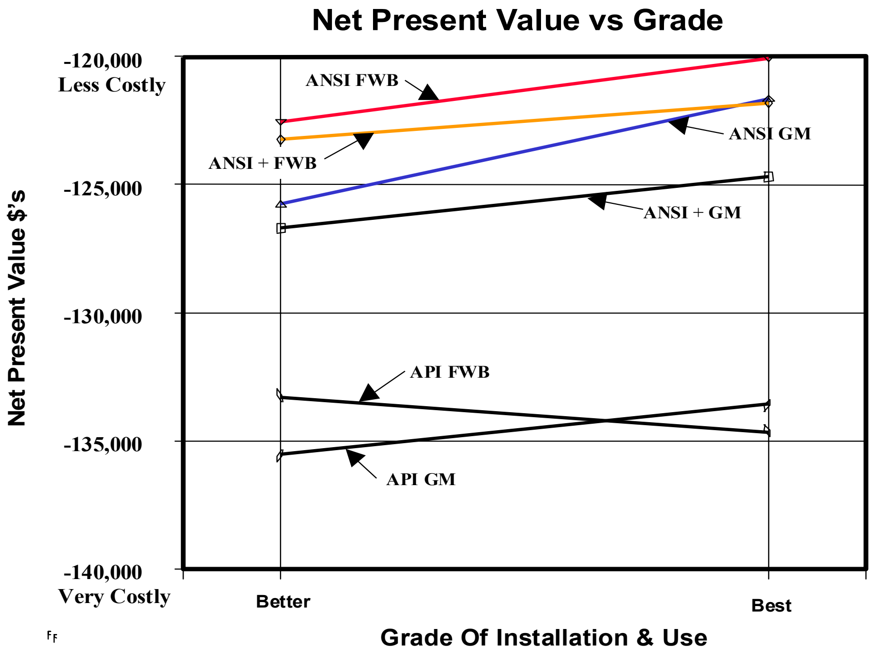


Figure 19: Breakeven Chart For NPV--Dual Pumps

Figure 20 shows the tradeoff plot of NPV versus effectiveness for better and best installation/use practices. Three alternatives represent slightly inferior values of NPV at substantially better values of system effectiveness.

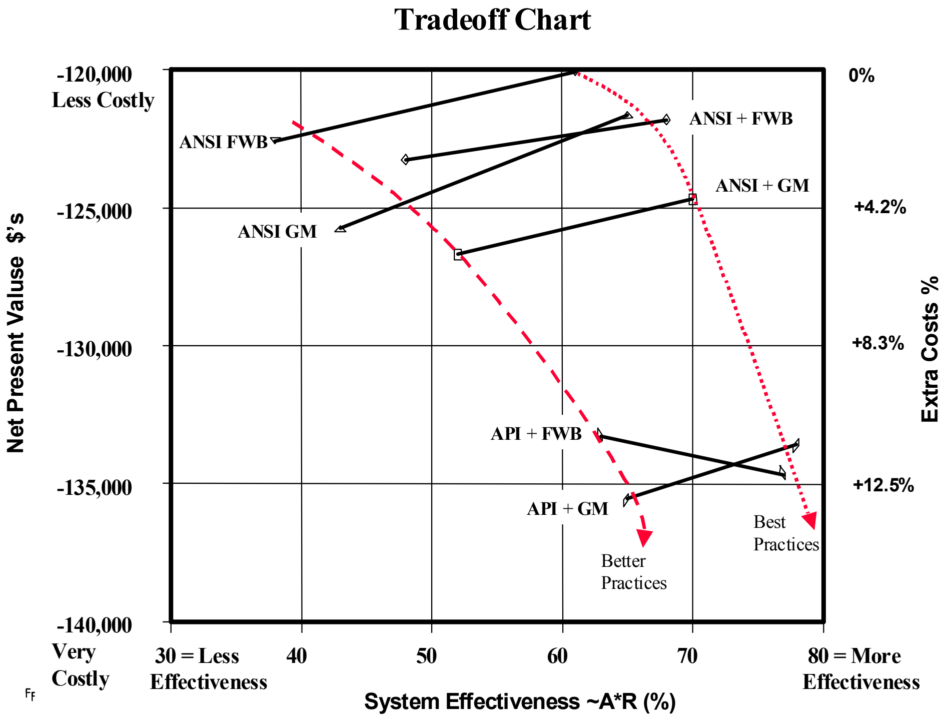


Figure 20: Tradeoff Chart

Figure 20 provides a sales tool for conveying information concerning tradeoffs for the selection of the equipment. The good practice category lies far to the lower left-hand corner of Figure 10's values.

The ANSI enhanced dual pumps installed/used with best practices and maintained with good maintenance practices will be selected as the tradeoff condition based on reasonable costs and reasonable system effectiveness which is paced by the reliability factor.

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.

Figure 21 shows a Pareto chart for ANSI enhanced dual pumps installed/used with best practices and good maintenance practices. One item consists of the vital few--electrical power!

Notice the Pareto distribution is shown in NPV terms to see the financial effects. The main issue is power consumption for this large horsepower pump. For this scenario, maintenance costs fall into the trivial portion of cost considerations.

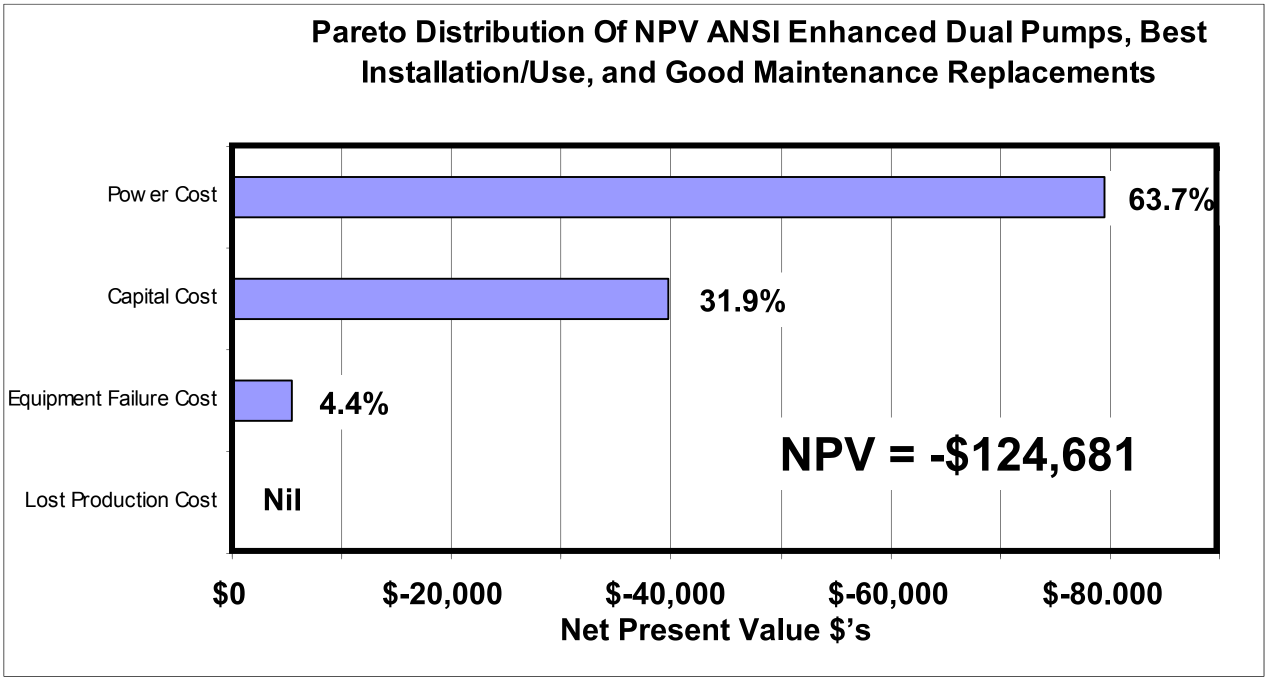


Figure 21: Pareto Distribution Based On Net Present Value

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

Sensitivity analysis allows study of key parameters on LCC--power consumption. Power consumed is a direct result of work performed, energy lost in inefficient motors/bearings, and energy lost in pump dynamics. High efficiency components can reduce poser consumption.

Energy savings by use of high efficiency motors can save about 3% of the total poser cost.

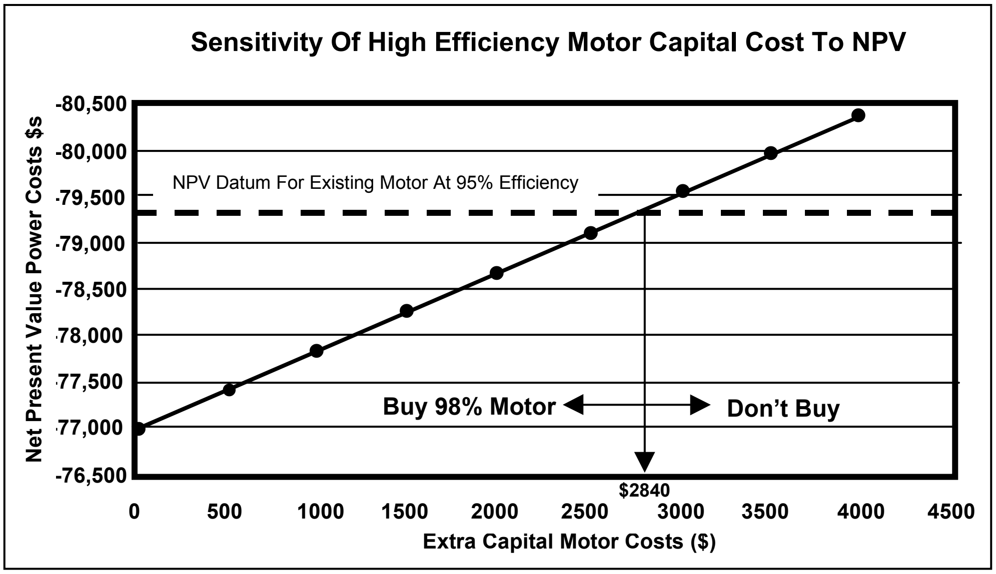


Figure 22: High Efficiency Motor Costs

Consider the sensitivity of extra capital cost for procuring 98% efficiency motors versus the standard 95% efficient motors. Figure 22 shows the break-even point for the extra procurement cost of the 100 horsepower motor.

Energy savings by choosing high efficiency internals for the pumps can save another 1.5% of the total poser cost. Consider the sensitivity of extra capital cost for procuring 86.5% efficiency pump internals versus the standard 85% efficient pump. This curve will be very close to the motor curse shown in Figure 22 and will be left for the reader to reproduce.

Another sensitivity issue is effectiveness as shown by reliability and availability. This has some bearing on the selection of the alternatives from the top 10 list in Figure 19. The details of each item are shown in Figure 23 as this has some sensitivity for how well things will perform over time.

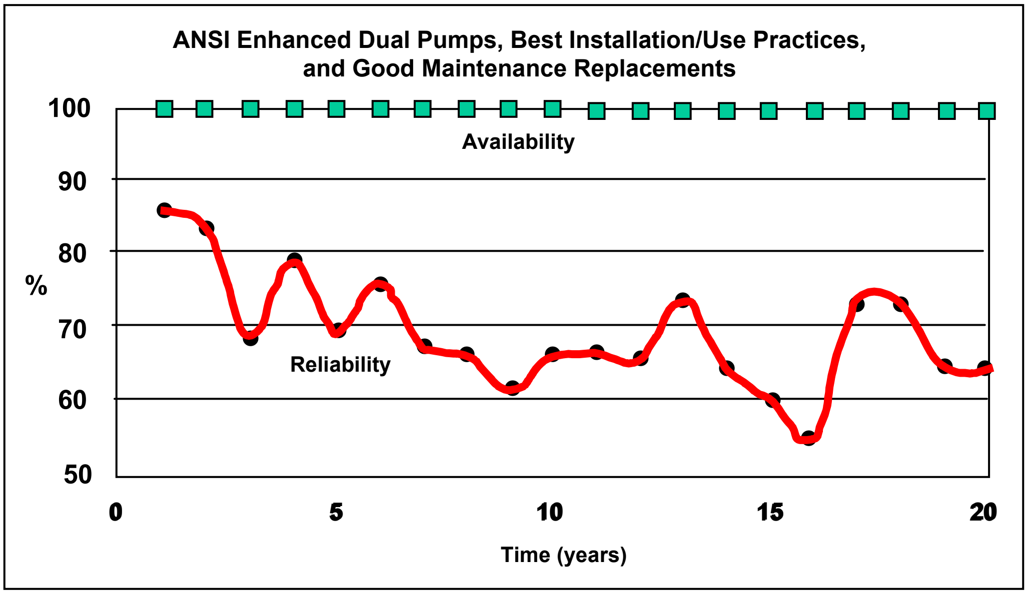


Figure 23: Availability and Reliability

The availability shown in Figure 23 is very high and unremarkable because repairs are made quickly and the redundant pumps protect the system from failures. Remember that availability is uptime/(uptime + downtime).

The one-year reliability curve in Figure 23 shows the rhythms of replacement and the general deterioration that occurs with time as found from the Monte Carlo simulation of failures and replacements. Remember reliability is a measure of the probability for a failure free interval.

Another area that is sensitive in many organizations is the number of equipment downtime hours expended by the maintenance department each year for equipment. The Monte Carlo simulation provides this information and it is presented in Figure 24.

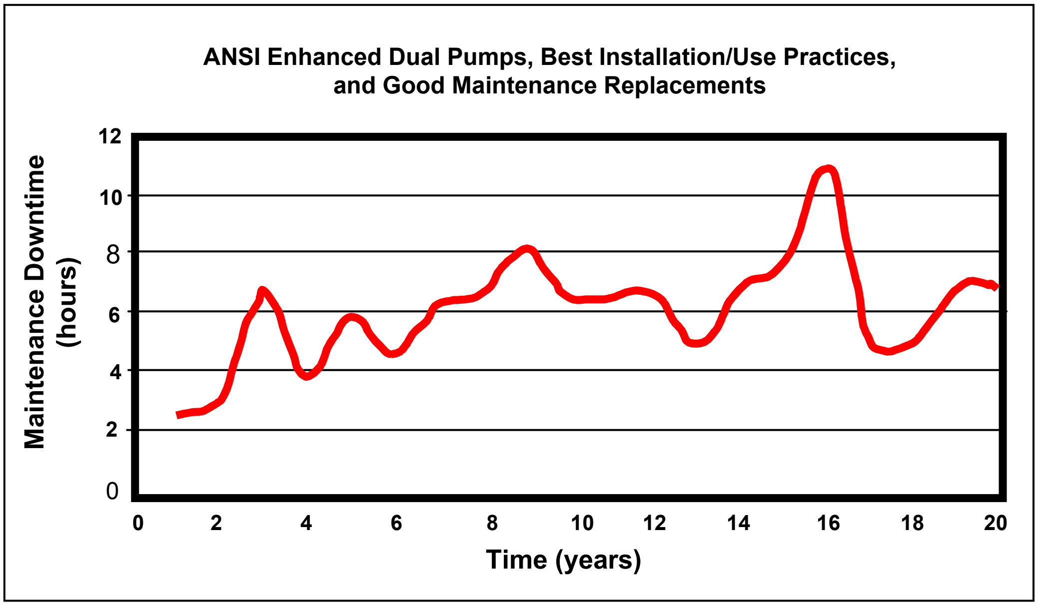


Figure 24: Maintenance Downtime

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 unreliability. Purchase 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.

SUMMARY

Life-cycle costs include cradle to grave costs. When failure costs are included, the quantity of manpower required could be engineered to avoid rules of thumb about how maintenance budgets are established. Adding installation and operating practices and their cost consequences to LCC adds reality to equipment selection.

LCC techniques provide methods to consider trade-off ideas. The LCC tradeoff visualization techniques are helpful for engineers. Likewise LCC analysis provides NPV techniques of importance for financial organizations. LCC details give engineering and financial groups common ground for communication.

For the same physical equipment can produce different LCC results in different organizations from use of different cost numbers, discount rates, and a host of other details. It is important to make local calculations to find the correct solution for the specific requirement.

All equipment has an inherent reliability, which results in a base failure rate. The installation and use practice alters the base failure rate to produce the expected failure rate for a particular operation. The examples shown above show techniques for addressing a series of engineering alternatives and finding the results through use of financial techniques. This method "prices out" the costs of practices in a manner that is helpful to engineers.

Clearly it is the responsibility of engineering departments to define equipment failure rates and the consequences of engineering practices on the life of equipment. Also it is the responsibility of engineers to convert the results of equipment life and failures into a financial format for clearly communicating the financial results within the organization. In commercial enterprises, it is not helpful for the engineering department to be technical smart but business ignorant since the reason for most commercial organizations is to make money. 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.

Remember the LCC calculations shown above were shortened to provide only the direct acquisition costs and direct sustaining costs, i.e., the details of what is missing and why are shown on page 14.

A limited subset of the LCC program written in Excel for calculation of the above details will be posted for free download from the World Wide Web (Barringer 1998) in June 1998.

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