Life Cycle Cost & Reliability for Process Equipment

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8th Annual **ENERGY WEEK** Conference & Exhibition

George R. Brown Convention Center
Houston, Texas

January 28-30, 1997

Organized by
American Petroleum Institute,

American Society of Mechanical Engineers,
and
PennWell Publishing

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ABSTRACT

Life cycle costs (LCC) are cradle-to-grave costs summarizing all ownership costs. Reliability plays an important role in selection of equipment for lowest long term cost of ownership. Results of a Monte Carlo simulation using an Excel™ spreadsheet show good maintenance practices (GMP) can alter outcomes of both cost and reliability. Maintenance strategies are shown for an API pump using LCC.

LIFE CYCLE COST DEFINITIONS

Life cycle costs are summations of estimated cost from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during the life of equipment or projects (Barringer 1996a). 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 while considering cost elements which include design, development, production, operation, maintenance, support, and final disposition of a major system over its anticipated useful life span. LCC is the sum of acquisition, logistic support and operating expenses (Landers 1996). LCC is the language of money (Goble 1992).

LCC analysis helps engineers justify equipment and process selection based on total costs rather than the initial purchase price as the cost of operation, maintenance, and disposal costs exceed all other costs many times over. Details of LCC have been recently summarized in a tutorial which includes an extensive listing of references (Barringer 1996b).

INTRODUCTION

Procurement costs are widely used as the primary (and sometimes only) criteria for selecting equipment or systems. This simple criteria is easy to use but often results in bad financial long term decisions. Procurement costs tell only one part of the story and equipment maintenance tells the rest of the story as equipment failure cost is often many times larger than procurement costs. Procurement of cheap equipment often increases maintenance costs and results in greater LCC. Complete cost details over the life of the equipment are needed for smart financial decisions, and this requires use of failure details, simulations, and net present value calculations.

WHY USE LCC?

LCC emphasizes economic competitiveness by working for the lowest long term cost of ownership. LCC requires many viewpoints to produce cost numbers and thus a teamwork approach is needed for minimizing LCC. When properly used (along with good engineering judgment), LCC provides a rich set of information for making cost effective, long term decisions in a disciplined manner.

LCC uses net present value (NPV) concepts. NPV is an important economic measure for projects or equipment taking into account discount factors, cash flow, and time. 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. Cash availability and strategies aside, when competing projects are judged for acceptance, projects with high NPVs usually win.

Engineers must be concerned with life cycle costs for making important economic decisions through engineering actions. This requires consideration of how and when sustaining costs occur during the life cycle of the equipment or project. Adding expected equipment failure rates and renewals from a statistical viewpoint makes analysis about economics smarter and gets the rational decisions closer to real world conditions. Engineers must supply facts (not opinions) for LCC calculations and LCC failures occur where teamwork is talked about but not practiced.

WHAT GOES INTO LIFE CYCLE COSTS?

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

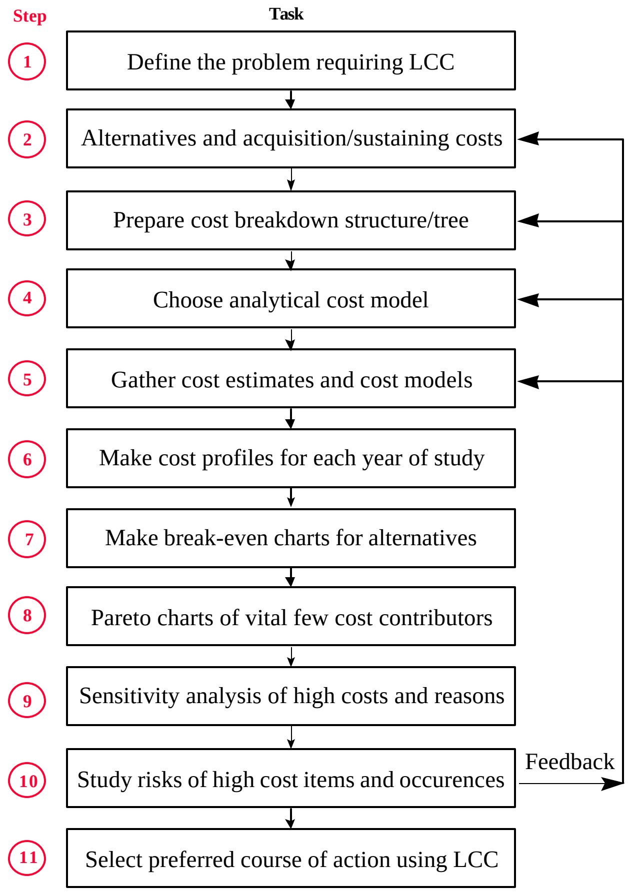


Figure 1: Life Cycle Costing Process

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

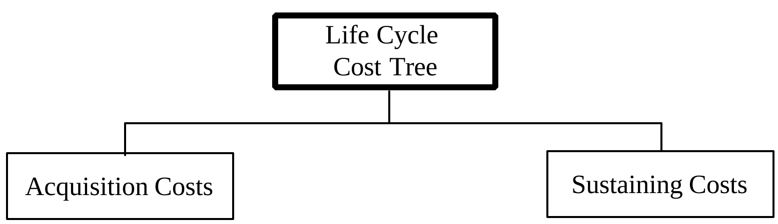


Figure 2: Top Levels Of LCC Tree

Frequently the cost of sustaining equipment is 2 to 20 times the acquisition cost. Consider the cost for a simple, continuously operating, pump—the power cost for driving the pump is many times larger than the acquisition cost of the pump. This means pumps must be procured with an emphasis on energy efficient drivers and energy efficient rotating parts while incurring modest increases in procurement costs to save large amounts of money over the life of the equipment. Here is an often cited rule of thumb: 65% of the total LCC is set when the equipment is specified!! As a result, do not consider specification processes lightly—unless you can afford it.

Every example has its own unique set of costs and problems to solve for minimizing LCC using acquisition and sustaining costs details. Each branch of acquisition and sustaining costs depends on the specific case and is generally driven by common sense. Include the appropriate cost elements and discard the elements which do not substantially influence LCC. SAE (SAE 1993) has a LCC model directed toward a manufacturing environment as shown in Figure 3.

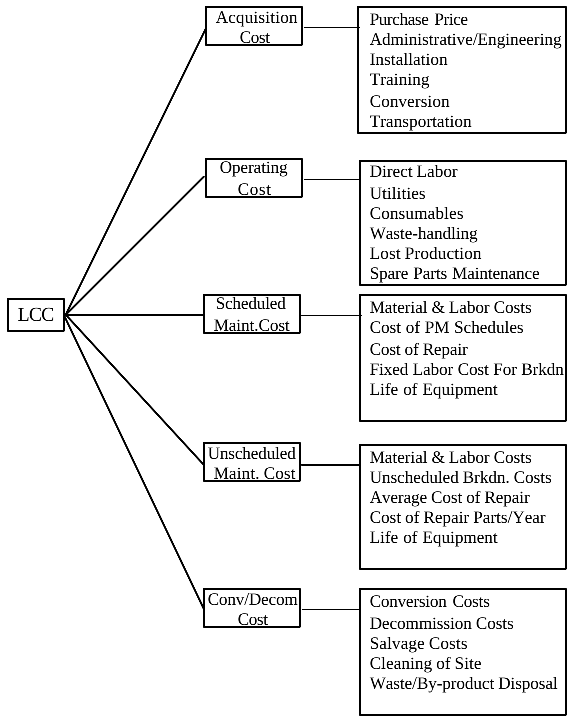


Figure 3: SAE Model of LCC

LCC varies with events, time, and conditions. Many cost variables are not deterministic but are probabilistic. This usually requires starting with arithmetic values for cost and then growing the cost numbers into more accurate, but more complicated, probabilistic values.

TRADE-OFF TOOLS FOR LCC

One helpful tool for easing LCC calculations is the effectiveness equation as a figure-of-merit. The effectiveness equation is described in several different formats (Barringer 1996b) where each element varies as a probability. The main issue is finding the best system effectiveness.

System effectiveness is an index of value. Value is a measure of relative desirability to create satisfaction divided by the price (Ireson 1996). The system effectiveness equations uses LCC as the quantity of price and effectiveness as the quantity measure of results received:

System effectiveness = Effectiveness/LCC

Effectiveness is a measure of relative desirability 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

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:

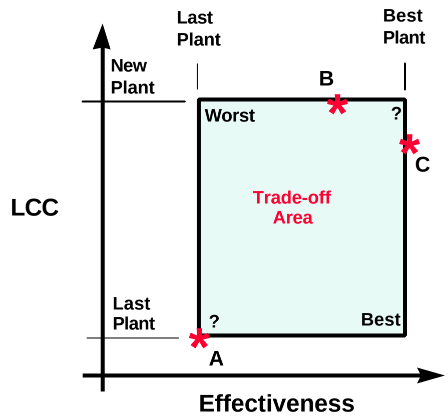
Availability deals with the duration of up-time for operations and is a measure of *how often* the system is alive and well. It is often expressed as (up-time)/(up-time + downtime) with many different variants. Availability issues deal with at least three main factors (Davidson 1988) for: 1) increasing 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 the higher the availability, the greater is the capacity for making money because the equipment has higher in-service life.

Reliability deals with reducing failures over a time interval and is a measure of *the odds 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 failure rate and MTBF is mean time between failure. MTBF measures how often the system will fail. MTBF is a basic figure-of-merit for reliability (or failure rate which is the reciprocal of MTBF) for exponential failure modes. End users of a product measure reliability by problem-free operation (resulting in increased productive capability while requiring fewer spare parts and less manpower for maintenance activities which results in lower costs). Suppliers of products measure reliability by completing a failure free warranty period under specified operating conditions. Improving reliability occurs at an increased capital cost but brings the expectation for improving availability, decreasing downtime and associated maintenance costs, improved secondary failure costs, and results in a better chance for making money because the equipment is free from failures for longer periods of time.

Maintainability deals with duration of maintenance downtime outages or *how long* it takes to achieve the maintenance actions compared to a datum. A key figure of merit is often the mean time to repair (MTTR) which measures maintenance outages. On a qualitative basis it refers to the ease with which hardware or software is restored to a functioning state and has probabilities as described for availability. Maintainability is measured based on the total down time which includes all diagnosis, trouble shooting, tear-down, removal/replacement, active repair time, verification that the repair is adequate, time delays for logistic movements, and administrative maintenance delays. It is often expressed as $R(t) = \exp(-t/MTTR) = \exp(-\mu t)$ where μ is maintenance rate and MTTR is mean time for maintenance actions. MTTR measures how quickly the system is returned to service and is a basic figure-of-merit for maintainability (or maintenance rate which is the reciprocal of μ) for exponential repair modes—however, most repairs are log-normally distributed.

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 such as (Actual Output)/(Name Plate Output). Utilization is the ratio of time spent on productive efforts to the total time consumed such as (Actual Hours Used)/(Maximum Hours Potential).

System effectiveness equations are helpful for understanding benchmarks, past, present, and future as shown in Figure 4. This provides an understanding for trade-off information.



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 4: Benchmark Data Shown In Trade-Off Format

Point A is preferred for cost compared to point B and point C. However, point C may be worth more than point A, and if this is true, then point C is more desirable than point A or point B. Point B is undesirable compared to point C and may not be worth the extra cost of point A.

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 1994 and 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 details (Barringer 1995).

Follow the guidelines for each step listed in Figure 1, for working-out a typical engineering problem shown below (remember, a single right or wrong method/solution does not exist--many methods and routes can be used to find LCC). Substitute your own values determined by local operating conditions, local costs, and local grades of equipment for your specific case.

Step 1: Define the problem. An API pump will operating without an online spare at 100 horsepower, 1750 RPM, 250 psi, 500 gpm, 70% hydraulic efficiency, while pumping fluid with a specific gravity of 1. 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$10,000/hour of outage.

Find an effective LCC alternative for maintenance strategies as the plant has an estimated 10 years life and the plant will be sold-out during this interval. Find the most cost effective maintenance strategy from two alternatives: 1) Without good maintenance practices, and 2) With good maintenance practices. Also show cost effects when no loss of gross margins occurs.

Step 2: Alternatives and acquisitions/sustaining costs. Consider two obvious alternatives for LCC based only on maintenance strategies (other alternatives exist for solving this problem more effectively, however, the list is pared for brevity):

> **Case 1:** Fix when broken strategy replacing only the broken part.
>
> **Case 2:** Good maintenance practices repair/replace the broken part plus replace additional items whose remaining life is short. For example, on a pump, when seals fail, also replace bearings, etc., to prevent pending failures.

Step 3: Prepare cost breakdown structure/tree.

The cost elements expected for each case are:

> **Case 1: Fix Only What's Broken**
> Acquisition costs = $18,000 installed and no other acquisition costs are involved as this is a standard pump which has already been documented and engineered.
>
> Sustaining costs include: Labor, materials, & overhead; replacement & renewal costs; replacement & renewal transportation costs; energy costs & facility usage costs; support & supply management costs; operations costs; ongoing training for maintenance & operations, permits & legal costs for equipment disposal; wrecking & disposal costs; remediation costs for disposal; write-off & asset recovery costs; and green & clean costs for other disposal items.
>
> **Case 2: Fix When Broken Along With Good Maintenance Practice**
> Acquisition costs = same as case 1
> Sustaining costs = case 1 but with the expectation that cost values will be different because extra parts are installed to prevent pending failures.

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 found by Monte Carlo simulation (Abernethy 1996) for each year and includes the uncertainty of when failures may occur. Five Monte Carlo runs were made and each had 3000 iterations. Results of the five runs were averaged to smooth results (this technique can also give standard deviations describing scatter in the data). Averaging the results of multiple runs can smooth scatter in the results but it also smoothes-out replacement rhythms of the system and hides the usual damping of system replacements. All simulated annual failure costs were found using the Monte Carlo simulation model for LCC available from the world wide web (Barringer 1996c). Weibull data is available from many sources (Barringer 1996d, Weber 1996a and 1996b).

Step 5: Gather cost estimates and cost models.

This section is complicated because cost details are assembled. Of course the more thorough the collection process, the better the LCC model—however for brevity, the details have been shortened with enough just information described to show the trends.

Case 1: Fix when broken: Use the following details in Table 1 gathered from plant experience an presented in a Weibull analysis format describing the predominate failure mode (no effort is made to describe common cause failures, rare events, or mixed failure modes, etc.). Use an accounting principle that costs will follow activity—in this case, costs will follow failure activity.

Capital cost are US$18,000, and lost gross margin occurs at US$10,000/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$16,500 as shown in Table 1.

Pump seals have Weibull values: (shape factor) β = 1.4, and (characteristic life) η = 4.5 years. When seal failure occurs, 8 hours of downtime is also lost production time at US$10,000/hour when the process is down for repairs. Maintenance crew costs for labor, incidental materials, and expense are US$100/hr (i.e., two people at US$50/hr each). Seal replacement costs are US$2,500/seal. Seal transportation costs are usually expedited and cost US$75 per incident. Find the annual pump seal costs (including lost production time for seal failures) by simulation as shown in Table 1. In a similar fashion, other component cost calculations are summarized in Table 1 along with other routine costs for PM and PdM efforts.

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 shown in Table 1.

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 shown in Table 1.

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 Department PM costs are: (52 visits*0.2hr/visit)*US$50/hr = US$520 as shown in Table 1.

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 an elapsed time of 0.5 hours. Annual training costs are: (0.5 hr * (3people*US$50 +3people*US$35)) = US$128 as shown in Table 1.

Table 1: Summary Of Cost Components For Fix When Broken

Raw Data	Variable Data		Variable Data		Weibull Data Variable Data		Costs Per Incident					
	Item Cost US$	Logistics Cost US$	Elapsed Repair or Activity hours	Activity Cost US$/hr	β	η	Maint. L&E US$	Replaced Part Cost US$	Logistics Costs US$	Lost Gross Margin US$	Total Cost Per Outage US$	**Annual Costs US$**
Electrical costs=	--	--	--	--	--	--	--	--	--	--	--	$ 16,500
Seal cost=	$ 2,500	$ 75	8	100	1.4	4.5	800	$ 2,500	$ 75	$ 80,000	$ 83,375	
Shaft cost=	$ 3,500	$ 300	10	100	1.2	22	1,000	$ 3,500	$ 300	$ 100,000	$ 104,800	
Impeller cost=	$ 3,500	$ 300	8	100	2.5	16	800	$ 3,500	$ 300	$ 80,000	$ 84,600	
Pump housing=	$ 4,500	$ 1,000	14	100	1.3	22	1,400	$ 4,500	$ 1,000	$ 140,000	$ 146,900	
Bearings cost=	$ 400	$ 75	8	100	1.3	6	800	$ 400	$ 75	$ 80,000	$ 81,275	
Motor cost=	$ 3,000	$ 500	8	100	1.2	12	800	$ 3,000	$ 500	$ 80,000	$ 84,300	
Coupling cost=	$ 1,200	$ 300	8	100	2	20	800	$ 1,200	$ 300	$ 80,000	$ 82,300	
Maintenance PM costs=			12	50								$ 600
Operations PM costs=			10.4	35								$ 364
Vibration Dept PdM costs=			10.4	50								$ 520
Training costs=			0.5	255								$ 128
												$ 18,112

Lost gross margin US$/hr =	$ 10,000
Power cost(US$165/hp-yr)=	$ 165
Motor size(hp)=	100

All sustaining cost inputs are summarized as shown in Table 1 and will be propagated forward for each year of the project using Monte Carlo techniques. Note the costs include the high cost of lost gross margin assigned to the failed element using the principle that costs follow activity.

Table 2 summarizes Monte Carlo failures for annual sustaining costs using facts from Table 1. Random failure times are drawn using the Weibull data from Table 1. The failures are accumulated by component and year of failure. When each part fails, a new part is installed and the age to failure clocks continue to wind-down until the next failure occurs, and thus the cycle is repeated. Optimum replacement intervals for preventive maintenance (PM) replacements are not appropriate as the pumps are in continuous service, and planned replacement cost is about the same as unplanned replacement cost and thus motivation for PM is lacking.

The results of all failures and their costs are found in Table 2. Note that Table 2 is the average of 5 Monte Carlo trials. Each trial contains 3000 iterations and each iterations is equivalent to 10 years of failure results. Thus 3000 iterations produces the equivalent of 30,000 years of operation. Furthermore the five trials give the average results from 150,000 years of operation! Table 2 shows increasing failures each year, generally increasing costs, and declining annual reliability. These results seem to parallel experiences in operating plants as older equipment is generally considered to be less cost effective and less reliable. The question in real life is how to quantify the results--the answer lies in Monte Carlo simulations and Weibull databases.

Table 2: Annual Sustaining Cost Summary Using A Strategy of Fix When Broken

Average of 5 trials at 3000 iterations/trial:

Average Down Time Hours For All Iterations=			2.680	3.779	4.477	4.789	5.141	5.258	5.591	5.554	5.863	5.855
Average Number Of Failures/year For All Iterations=			0.314	0.444	0.527	0.563	0.605	0.618	0.658	0.653	0.689	0.690
Annual Cost Expected For Each Time Interval			Project Year And Annual Costs Expected From Simulation									
	Cost Element	0	1	2	3	4	5	6	7	8	9	10
	Electricity		$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500
	Seal		$ 10,138	$ 14,785	$ 17,581	$ 18,582	$ 20,016	$ 19,710	$ 20,366	$ 20,054	$ 20,688	$ 20,227
	Shaft		$ 2,543	$ 3,151	$ 3,780	$ 3,857	$ 4,457	$ 4,143	$ 4,304	$ 4,115	$ 4,548	$ 4,590
	Impeller		$ 85	$ 417	$ 852	$ 1,359	$ 1,726	$ 2,425	$ 3,141	$ 3,987	$ 4,207	$ 4,986
	Housing		$ 2,899	$ 4,005	$ 4,642	$ 5,122	$ 5,259	$ 5,710	$ 6,062	$ 6,072	$ 6,513	$ 5,974
	Pump Bearings		$ 7,662	$ 10,766	$ 12,836	$ 13,096	$ 13,573	$ 13,703	$ 14,266	$ 14,088	$ 14,489	$ 14,673
	Motors		$ 4,288	$ 5,474	$ 5,811	$ 6,233	$ 6,648	$ 6,722	$ 7,222	$ 6,705	$ 7,351	$ 6,856
	Coupling		$ 198	$ 209	$ 218	$ 232	$ 239	$ 253	$ 267	$ 266	$ 279	$ 290
	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 PdM		$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520
	Training costs		$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128
	Total=		$ 45,924	$ 56,920	$ 63,831	$ 66,592	$ 70,030	$ 70,776	$ 73,740	$ 73,399	$ 76,186	$ 75,707
Approximate suspensions per failure=			0	0	0	0	0	0	0	0	0	0
Approximate system failure rate (failures/yr)=			0.314	0.444	0.527	0.563	0.605	0.618	0.658	0.653	0.689	0.690
Approximate system MTBF(years/failure) =			3.184	2.251	1.899	1.776	1.653	1.618	1.521	1.532	1.453	1.449
Theoretical 1 yr Reliability =			72.92%									
1 yr reliability, R=			73.04%	64.12%	59.05%	56.94%	54.60%	53.90%	51.81%	52.04%	50.23%	50.14%
Fix When Broken Strategy	1 yr Availability, A=		99.97%	99.96%	99.95%	99.95%	99.94%	99.94%	99.94%	99.94%	99.93%	99.93%

Disposal costs will occur as a lump at the end of the ten year remaining life. The costs include: 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. Disposal costs occur in the final year.

Table 3 collects both acquision/disposal costs and the sustaining costs in a single table.

Table 3: Summary Of Acquisition & Sustaining Costs For Fix When Broken

Acquisition + Sustaining Costs

	Project Year And Annual Costs Expected From Simulation											
Cost Element	0	1	2	3	4	5	6	7	8	9	10	**Total**
Acquisition	$18,000											$18,000
Electricity		$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$165,000
Seal		$ 10,138	$ 14,785	$ 17,581	$ 18,582	$ 20,016	$ 19,710	$ 20,366	$ 20,054	$ 20,688	$ 20,227	$182,147
Shaft		$ 2,543	$ 3,151	$ 3,780	$ 3,857	$ 4,457	$ 4,143	$ 4,304	$ 4,115	$ 4,548	$ 4,590	$39,489
Impeller		$ 85	$ 417	$ 852	$ 1,359	$ 1,726	$ 2,425	$ 3,141	$ 3,987	$ 4,207	$ 4,986	$23,186
Housing		$ 2,899	$ 4,005	$ 4,642	$ 5,122	$ 5,259	$ 5,710	$ 6,062	$ 6,072	$ 6,513	$ 5,974	$52,257
Pump Bearings		$ 7,662	$ 10,766	$ 12,836	$ 13,096	$ 13,573	$ 13,703	$ 14,266	$ 14,088	$ 14,489	$ 14,673	$129,151
Motors		$ 4,288	$ 5,474	$ 5,811	$ 6,233	$ 6,648	$ 6,722	$ 7,222	$ 6,705	$ 7,351	$ 6,856	$63,309
Coupling		$ 198	$ 209	$ 218	$ 232	$ 239	$ 253	$ 267	$ 266	$ 279	$ 290	$2,452
Maintenance PM visits		$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$6,000
Operations PM visits		$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$3,640
Vibration Dept PdM		$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$5,200
Training costs		$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$1,275
Disposal											$ 3,000	$3,000
Total=	$18,000	$ 45,924	$ 56,920	$ 63,831	$ 66,592	$ 70,030	$ 70,776	$ 73,740	$ 73,399	$ 76,186	$ 78,707	$694,106

Data from Table 3 must be discounted to reach to measure future money values in present day terms. The discount rates simply say a bird in the hand today is worth the promise of two birds in the bush six years from now! Assume the use of a 12% discount rate to get the values shown in Table 4 in present values.

Table 4 shows costs in present day values so that the time value of money has been corrected for a uniform comparison.

Table 4: Discounted Values For Acquisition & Sustaining Costs For Fix When Broken

Discounted Values of Acquisition + Sustaining Costs @ 12%

Cost Element	0	1	2	3	4	5	6	7	8	9	10	Total
Present value of US$1	1.00	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	
	Project Year And Annual Costs Expected From Simulation											
Acquisition	$18,000											$18,000
Electricity		$ 14,685	$ 13,200	$ 11,715	$ 10,560	$ 9,405	$ 8,415	$ 7,425	$ 6,600	$ 5,940	$ 5,280	$93,225
Seal		$ 9,023	$ 11,828	$ 12,483	$ 11,892	$ 11,409	$ 10,052	$ 9,165	$ 8,022	$ 7,448	$ 6,473	$97,794
Shaft		$ 2,263	$ 2,521	$ 2,684	$ 2,468	$ 2,541	$ 2,113	$ 1,937	$ 1,646	$ 1,637	$ 1,469	$21,279
Impeller		$ 75	$ 334	$ 605	$ 870	$ 984	$ 1,237	$ 1,414	$ 1,595	$ 1,515	$ 1,595	$10,223
Housing		$ 2,580	$ 3,204	$ 3,296	$ 3,278	$ 2,998	$ 2,912	$ 2,728	$ 2,429	$ 2,345	$ 1,912	$27,681
Pump Bearings		$ 6,819	$ 8,613	$ 9,114	$ 8,382	$ 7,737	$ 6,989	$ 6,420	$ 5,635	$ 5,216	$ 4,695	$69,618
Motors		$ 3,816	$ 4,379	$ 4,126	$ 3,989	$ 3,790	$ 3,428	$ 3,250	$ 2,682	$ 2,646	$ 2,194	$34,300
Coupling		$ 176	$ 167	$ 155	$ 149	$ 136	$ 129	$ 120	$ 107	$ 100	$ 93	$1,332
Maintenance PM visits		$ 534	$ 480	$ 426	$ 384	$ 342	$ 306	$ 270	$ 240	$ 216	$ 192	$3,390
Operations PM visits		$ 324	$ 291	$ 258	$ 233	$ 207	$ 186	$ 164	$ 146	$ 131	$ 116	$2,057
Vibration Dept PdM		$ 463	$ 416	$ 369	$ 333	$ 296	$ 265	$ 234	$ 208	$ 187	$ 166	$2,938
Training costs		$ 113	$ 102	$ 91	$ 82	$ 73	$ 65	$ 57	$ 51	$ 46	$ 41	$720
Disposal											$ 960	$960
Total=	$18,000	$ 40,872	$ 45,536	$ 45,320	$ 42,619	$ 39,917	$ 36,096	$ 33,183	$ 29,360	$ 27,427	$ 25,186	$383,516

Costs incurred, less acquisition, are $365,516 (including the high cost of lost gross margins for outages) which is 20 times larger than the acquisition cost of the pump at $18,500! On a Pareto basis, the vital few elements are centered in three categories as shown in Table 5—remember each failure carries with it the high costs for lost gross margins because of the failures.

Table 5: The Vital Few Items Of Importance For Fix When Broken

Cost Element	Total	Cum %	Priority
Seal	$97,794	25.5%	1
Electricity	$93,225	49.8%	2
Pump Bearings	$69,618	68.0%	3
Motors	$34,300	76.9%	
Housing	$27,681	84.1%	
Shaft	$21,279	89.7%	
Acquisition	$18,000	94.4%	
Impeller	$10,223	97.0%	
Maintenance PM visits	$3,390	97.9%	
Vibration Dept PdM	$2,938	98.7%	
Operations PM visits	$2,057	99.2%	
Coupling	$1,332	99.6%	
Disposal	$960	99.8%	
Training costs	$720	100.0%	
Total=	$383,516		

In the top items from Table 5, both seal costs and bearing costs are shown as high values because they are connected to the high cost of downtime. Each component failure is charged for the lost gross margin which follows their individual failures.

Finally, putting the data into a NPV calculation, Table 6 shows the expected NPV based on a tax rate of 38% and a straight line depreciation—of course the discount factor used in Table 6 is the reciprocal of the present value information shown in Table 4.

Table 6: Net Present Value Of Fix When Broken Strategy

NPV For API Pump--Fix When Broken Strategy
Straight line depreciation, 12% discount rate, 38% tax rate

	Year										
	0	1	2	3	4	5	6	7	8	9	10
API Pump--Fix When Broken Strategy											
Capital	18000										
Cost		45924	56920	63831	66592	70030	70776	73740	73399	76186	78707
Savings											
Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Profit b/4 taxes		-47724	-58720	-65631	-68392	-71830	-72576	-75540	-75199	-77986	-80507
Tax Provision		18135	22313	24940	25989	27295	27579	28705	28576	29635	30593
Net Income		-29589	-36406	-40692	-42403	-44535	-44997	-46835	-46623	-48352	-49915
Add Back Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Cash Flow	-18000	-27789	-34606	-38892	-40603	-42735	-43197	-45035	-44823	-46552	-48115
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	-18000	-24811	-27588	-27682	-25804	-24249	-21885	-20371	-18103	-16787	-15492
Net Present Value	**$ (240,773)**	using a 12% discount rate									

Case 2: Fix when broken using good maintenance practices: Many costs for this example are the same such as electricity and acquisition costs. The differences occur in extra expenditures for replacement parts at failure.

For example, good maintenance practices replace the primary failure but also replace other items:

When seals fail, also replace bearings
When bearings fail, also replace seals
When shafts fail, also replace seals and bearings
When impellers fail, also replace seals and bearings
When housings fail, also replace seals and bearings

The impact of these costs are shown in Table 7.

Extra replacements, for GMP, increase consumption of materials but usually do not extend the repair time. The reasons for spending the extra money is to increase equipment reliability and defer impending failures to avoid outages. An example of the extra costs follows.

Pump seals have Weibull values: (shape factor) β = 1.4, and (characteristic life) η = 4.5 years. When seal failure occurs, 8 hours of downtime is also lost production time at US$10,000/hour when the process is down for repairs. Maintenance crew costs for labor, incidental materials, and expense are US$100/hr (i.e., two people at US$50/hr each). Seal replacement costs are US$2,500/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. Find the annual pump seal costs (including lost production time for seal failures) by simulation as shown by cost inputs from Table 7. In a similar fashion, other component cost calculations are summarized in Table 7 along with other costs for PM and PdM efforts. Contrast GMP cost of Table 7 with Table 1.

Table 7: Summary Of Cost Components Using Fix When Broken + GMP

Raw Data For Fix When Broken Strategy Using GMP

	Variable Data		Variable Data		Weibull Data Variable Data		Costs Per Incident					
	Item Cost US$	Logistics Cost US$	Elapsed Repair or Activity hours	Activity Cost US$/hr	β	η	Maint. L&E US$	Replaced Part Cost US$	Logistics Costs US$	Lost Gross Margin US$	Total Cost Per Outage US$	**Annual Costs US$**
Electrical costs=	--	--	--	--	--	--	--	--	--	--	--	$ 16,500
Seal cost=	$ 2,500	$ 75	8	100	1.4	4.5	800	$ 2,900	$ 150	$ 80,000	$ 83,850	
Shaft cost=	$ 3,500	$ 300	10	100	1.2	22	1,000	$ 6,400	$ 450	$ 100,000	$ 107,850	
Impeller cost=	$ 3,500	$ 300	8	100	2.5	16	800	$ 6,400	$ 450	$ 80,000	$ 87,650	
Pump housing=	$ 4,500	$ 1,000	14	100	1.3	22	1,400	$ 7,400	$ 1,150	$ 140,000	$ 149,950	
Bearings cost=	$ 400	$ 75	8	100	1.3	6	800	$ 2,900	$ 150	$ 80,000	$ 83,850	
Motor cost=	$ 3,000	$ 500	8	100	1.2	12	800	$ 3,000	$ 500	$ 80,000	$ 84,300	
Coupling cost=	$ 1,200	$ 300	8	100	2	20	800	$ 1,200	$ 300	$ 80,000	$ 82,300	
Maintenance PM costs=			12	50								$ 600
Operations PM costs=			10.4	35								$ 364
Vibration Dept PdM costs=			10.4	50								$ 520
Training costs=			0.5	255								$ 128
												$ 18,112

Lost gross margin US$/hr =	$ 10,000
Power cost(US$165/hp-yr)=	$ 165
Motor size(hp)=	100

All sustaining costs are shown in Table 8 and will be put into appropriate time buckets using the Monte Carlo simulation technique for the strategy of fix when broken plus good maintenance practices. Notice in Table 8 when each item fails it carries the cost of outages and the loss of gross margin for the outage as shown in the column Total Cost Per Outage. Table 8 summarizes results of five Monte Carlo trials where 3000 iterations occur per trial and reflects the average of the five results to obtain the annual sustaining costs for each year.

Table 8: Annual Sustaining Cost Summary Using A Fix When Broken + GMP Strategy

Average of 5 trials at 3000 iterations/trial:

Average Down Time Hours For All Iterations=		2.611	3.743	4.193	4.398	4.567	4.677	4.819	4.989	4.959	5.094
›rage Number Of Failures/year For All Iterations=		0.307	0.440	0.492	0.515	0.535	0.548	0.563	0.582	0.579	0.593
Annual Cost Expected For Each Time Interval		Project Year And Annual Costs Expected From Simulation									
Cost Element	0	1	2	3	4	5	6	7	8	9	10
Electricity		$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500
Seal		$ 9,749	$ 14,909	$ 16,513	$ 16,507	$ 16,641	$ 16,200	$ 16,239	$ 16,144	$ 16,261	$ 15,898
Shaft		$ 2,739	$ 3,351	$ 3,825	$ 3,688	$ 3,990	$ 4,019	$ 4,458	$ 4,681	$ 4,422	$ 4,558
Impeller		$ 129	$ 456	$ 812	$ 1,385	$ 1,987	$ 2,799	$ 3,307	$ 4,125	$ 4,242	$ 5,031
Housing		$ 2,699	$ 3,969	$ 4,618	$ 5,218	$ 5,398	$ 5,418	$ 5,868	$ 6,258	$ 6,168	$ 6,578
Pump Bearings		$ 7,832	$ 10,587	$ 11,269	$ 11,588	$ 11,834	$ 12,130	$ 11,784	$ 11,532	$ 11,398	$ 11,845
Motors		$ 4,187	$ 5,553	$ 6,008	$ 6,497	$ 6,525	$ 6,643	$ 6,693	$ 7,188	$ 7,008	$ 6,800
Coupling		$ 199	$ 227	$ 262	$ 284	$ 304	$ 327	$ 352	$ 369	$ 375	$ 391
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 PdM		$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520
Training costs		$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128
Total=		$ 45,645	$ 57,162	$ 61,419	$ 63,279	$ 64,792	$ 65,648	$ 66,813	$ 68,408	$ 67,986	$ 69,214
Approximate suspensions per failure=		0	0	0	0	0	0	0	0	0	0
Approximate system failure rate (failures/yr)=		0.307	0.440	0.492	0.515	0.535	0.548	0.563	0.582	0.579	0.593
Approximate system MTBF(years/failure) =		3.265	2.272	2.033	1.942	1.871	1.825	1.778	1.720	1.729	1.685
Theoretical 1 yr Reliability =		72.92%									
1 yr reliability, R=		73.60%	64.39%	61.13%	59.75%	58.59%	57.80%	56.97%	55.91%	56.06%	55.25%
Good Maintenance Practices 1 yr Availability, A=		99.97%	99.96%	99.95%	99.95%	99.95%	99.95%	99.94%	99.94%	99.94%	99.94%

Table 9 summarizes the acquisition and sustaining cost details. The total costs using GMP are US$42,740 less than for the comparable results in Table 3 even with the inclusion of procurement and installation of components of unfailed (i.e., suspended data) parts.

Table 9: Summary Of Acquisition & Sustaining Cost Including GMP Strategy

Acquisition + Sustaining Costs For Fix When Broken + GMP Strategy

Cost Element	Project Year And Annual Costs Expected From Simulation											Total
	0	1	2	3	4	5	6	7	8	9	10	
Acquisition	$18,000											$18,000
Electricity		$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$ 16,500	$165,000
Seal		$ 9,749	$ 14,909	$ 16,513	$ 16,507	$ 16,641	$ 16,200	$ 16,239	$ 16,144	$ 16,261	$ 15,898	$155,061
Shaft		$ 2,739	$ 3,351	$ 3,825	$ 3,688	$ 3,990	$ 4,019	$ 4,458	$ 4,681	$ 4,422	$ 4,558	$39,732
Impeller		$ 129	$ 456	$ 812	$ 1,385	$ 1,987	$ 2,799	$ 3,307	$ 4,125	$ 4,242	$ 5,031	$24,273
Housing		$ 2,699	$ 3,969	$ 4,618	$ 5,218	$ 5,398	$ 5,418	$ 5,868	$ 6,258	$ 6,168	$ 6,578	$52,193
Pump Bearings		$ 7,832	$ 10,587	$ 11,269	$ 11,588	$ 11,834	$ 12,130	$ 11,784	$ 11,532	$ 11,398	$ 11,845	$111,800
Motors		$ 4,187	$ 5,553	$ 6,008	$ 6,497	$ 6,525	$ 6,643	$ 6,693	$ 7,188	$ 7,008	$ 6,800	$63,101
Coupling		$ 199	$ 227	$ 262	$ 284	$ 304	$ 327	$ 352	$ 369	$ 375	$ 391	$3,091
Maintenance PM visits		$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$6,000
Operations PM visits		$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$3,640
Vibration Dept PdM		$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$5,200
Training costs		$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$1,275
Disposal											$ 3,000	$3,000
Total=	$18,000	$ 45,645	$ 57,162	$ 61,419	$ 63,279	$ 64,792	$ 65,648	$ 66,813	$ 68,408	$ 67,986	$ 72,214	$651,366

Discounting data from Table 9 puts every cost number on present value basis using a 12% discount rate as shown in Table 10. The discounted total costs using GMP are US$19,632 ($384,016-$364,384) lower than comparable costs shown in Table 4—remember the extra costs for replacement of non-failed parts are included in the total costs.

Table 10: Discounted Values For Acquisition & Sustaining Cost Including GMP Strategy

Discounted Values of Acquisition + Sustaining Costs @ 12%

Present value of US$1	1.00	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	
	Project Year And Annual Costs Expected From Simulation											
Cost Element	0	1	2	3	4	5	6	7	8	9	10	Total
Acquisition	$18,000											$18,000
Electricity		$ 14,685	$ 13,200	$ 11,715	$ 10,560	$ 9,405	$ 8,415	$ 7,425	$ 6,600	$ 5,940	$ 5,280	$93,225
Seal		$ 8,677	$ 11,927	$ 11,724	$ 10,565	$ 9,486	$ 8,262	$ 7,308	$ 6,458	$ 5,854	$ 5,087	$85,346
Shaft		$ 2,438	$ 2,680	$ 2,716	$ 2,361	$ 2,275	$ 2,050	$ 2,006	$ 1,872	$ 1,592	$ 1,459	$21,448
Impeller		$ 114	$ 365	$ 577	$ 886	$ 1,132	$ 1,427	$ 1,488	$ 1,650	$ 1,527	$ 1,610	$10,778
Housing		$ 2,402	$ 3,175	$ 3,279	$ 3,340	$ 3,077	$ 2,763	$ 2,641	$ 2,503	$ 2,220	$ 2,105	$27,505
Pump Bearings		$ 6,970	$ 8,470	$ 8,001	$ 7,416	$ 6,745	$ 6,186	$ 5,303	$ 4,613	$ 4,103	$ 3,790	$61,599
Motors		$ 3,726	$ 4,442	$ 4,266	$ 4,158	$ 3,719	$ 3,388	$ 3,012	$ 2,875	$ 2,523	$ 2,176	$34,285
Coupling		$ 177	$ 182	$ 186	$ 182	$ 173	$ 167	$ 158	$ 147	$ 135	$ 125	$1,633
Maintenance PM visits		$ 534	$ 480	$ 426	$ 384	$ 342	$ 306	$ 270	$ 240	$ 216	$ 192	$3,390
Operations PM visits		$ 324	$ 291	$ 258	$ 233	$ 207	$ 186	$ 164	$ 146	$ 131	$ 116	$2,057
Vibration Dept PdM		$ 463	$ 416	$ 369	$ 333	$ 296	$ 265	$ 234	$ 208	$ 187	$ 166	$2,938
Training costs		$ 113	$ 102	$ 91	$ 82	$ 73	$ 65	$ 57	$ 51	$ 46	$ 41	$720
Disposal											$ 960	$960
Total=	$18,000	$ 40,624	$ 45,730	$ 43,608	$ 40,498	$ 36,931	$ 33,480	$ 30,066	$ 27,363	$ 24,475	$ 23,108	$363,884

The vital few Pareto elements from Table 10 are shown in Table 11.

Table 11: The Vital Few Items Of Importance Using GMP Strategies

Cost Element	Total	Cum %	Priority
Electricity	$93,225	25.6%	1
Seal	$85,346	49.1%	2
Pump Bearings	$61,599	66.0%	3
Motors	$34,285	75.4%	
Housing	$27,505	83.0%	
Shaft	$21,448	88.9%	
Acquisition	$18,000	93.8%	
Impeller	$10,778	96.8%	
Maintenance PM visits	$3,390	97.7%	
Vibration Dept PdM	$2,938	98.5%	
Operations PM visits	$2,057	99.1%	
Coupling	$1,633	99.5%	
Disposal	$960	99.8%	
Training costs	$720	100.0%	
Total=	$363,884		

Notice how the ranking and absolute values of the vital few items in Table 11 have changed by use of GMP compared to Table 5.

Finally, the net present value calculations are shown in Table 12.

Table 12: Net Present Value Of Fix When Broken + GMP Strategy

NPV For API Pump--Fix When Broken Strategy + GMP
Straight line depreciation, 12% discount rate, 38% tax rate

	Year										
	0	1	2	3	4	5	6	7	8	9	10
API Pump--Fix When Broken Strategy + GMP											
Capital	18000										
Cost		$ 45,645	$ 57,162	$ 61,419	$ 63,279	$ 64,792	$ 65,648	$ 66,813	$ 68,408	$ 67,986	$ 72,214
Savings											
Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Profit b/4 taxes		-47445	-58962	-63219	-65079	-66592	-67448	-68613	-70208	-69786	-74014
Tax Provision		18029	22406	24023	24730	25305	25630	26073	26679	26519	28125
Net Income		-29416	-36557	-39196	-40349	-41287	-41818	-42540	-43529	-43268	-45888
Add Back Depreciation		1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Cash Flow	-18000	-27616	-34757	-37396	-38549	-39487	-40018	-40740	-41729	-41468	-44088
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	-18000	-24657	-27708	-26618	-24499	-22406	-20274	-18429	-16854	-14954	-14195
Net Present Value	**$(228,592)**	using a 12% discount rate									

Note the NPV from Table 6 for a fix when broken (without use of GMP) shows US$(240,773) and the GMP strategy in Table 12 shows NPV = US$(228,592). GMP produces a savings of US$12,181 by avoiding pending failures even with inclusion of the higher costs of replacing parts that have not failed.

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 5. 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. A breakeven points does not exist as GMP is always better than the simple “fix when broken” strategy for this condition of lost gross margins when outages occur.

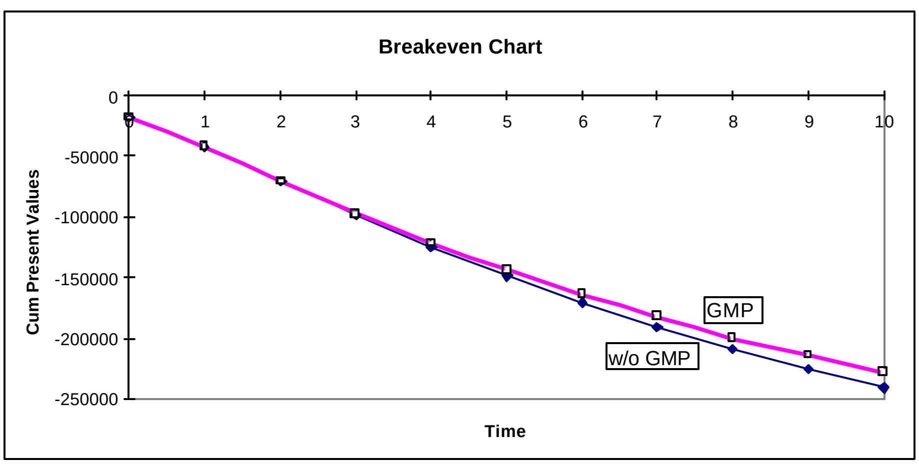


Figure 5: Breakeven Chart (GMP Is Always Better!)

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 fix when broken strategy are shown in Figure 6 and reflect the details of Table 5. Clearly the big three items are the vital few elements of concern.

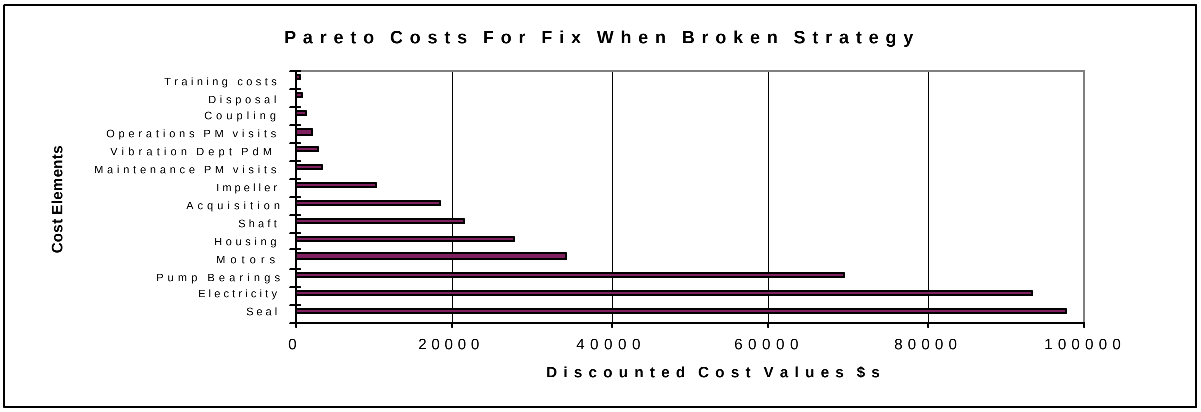


Figure 6: Pareto Cost Chart For Fix When Broken Strategy

When the maintenance strategy is improved by use of GMP, the absolute values decrease and the ranking changes somewhat—even though the big three items are the same for Figure 6 and Figure 7.

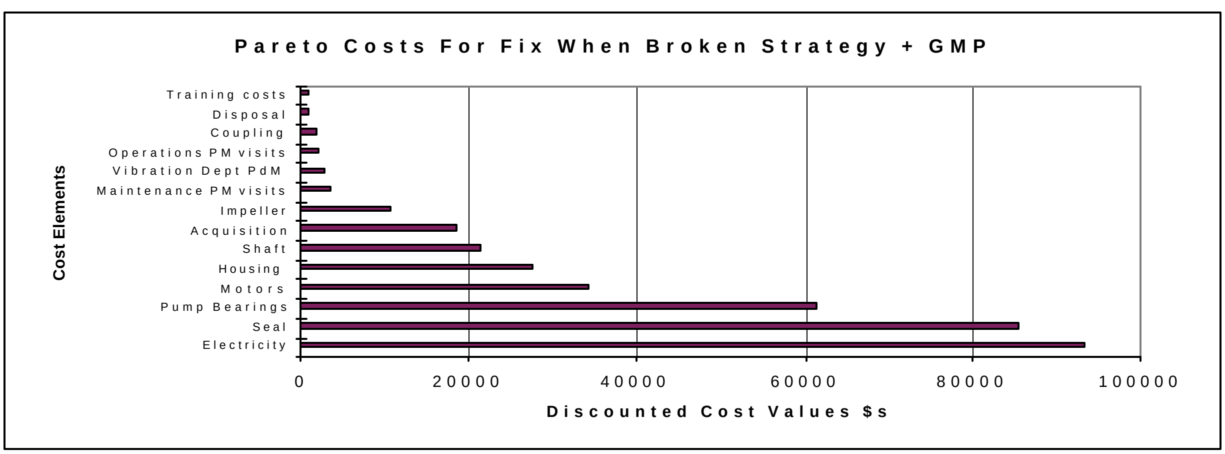


Figure 7: Pareto Cost Chart For Fix When Broken + GMP

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

Sensitivity analysis allows study of key parameters on LCC. Consider a few of the details shown in Table 2 and Table 8 using arithmetic to develop some numbers for analysis.

For Table 2, the average reliability is 56.59%, and the average availability is 99.94%. These numbers are associated with an LCC=NPV=($240773).

For Table 8 with GMP, the average reliability is 59.95%, and the average availability is 99.95%. These numbers are associated with an LCC=NPV=($228592).

Furthermore, assume maintainability = 80% for each case, and assume capability = 80% for each case. Thus the effectiveness equation for Table 2 is: 0.9994*0.5659*0.8*0.8 = 0.362. For Table 8 the effectiveness equation is: 0.9995*0.5995*0.8*0.8 = 0.383. In short, the main difference in the effectiveness equations is reliability (i.e, the odds are improved by GMP for a failure free interval)!

The details are shown in Figure 8 with GMP occupying a favorable position of better cost and greater effectiveness. The effectiveness improvement is essentially due to enhanced reliability values (see details in Tables 2 and 8) resulting from the GMP strategy. The difference between ~55% reliability and ~50% reliability shown in Figure 8 is a substantial difference when considering a (0.690 -0.593)/0.593 = 16.4% difference in failure rates.

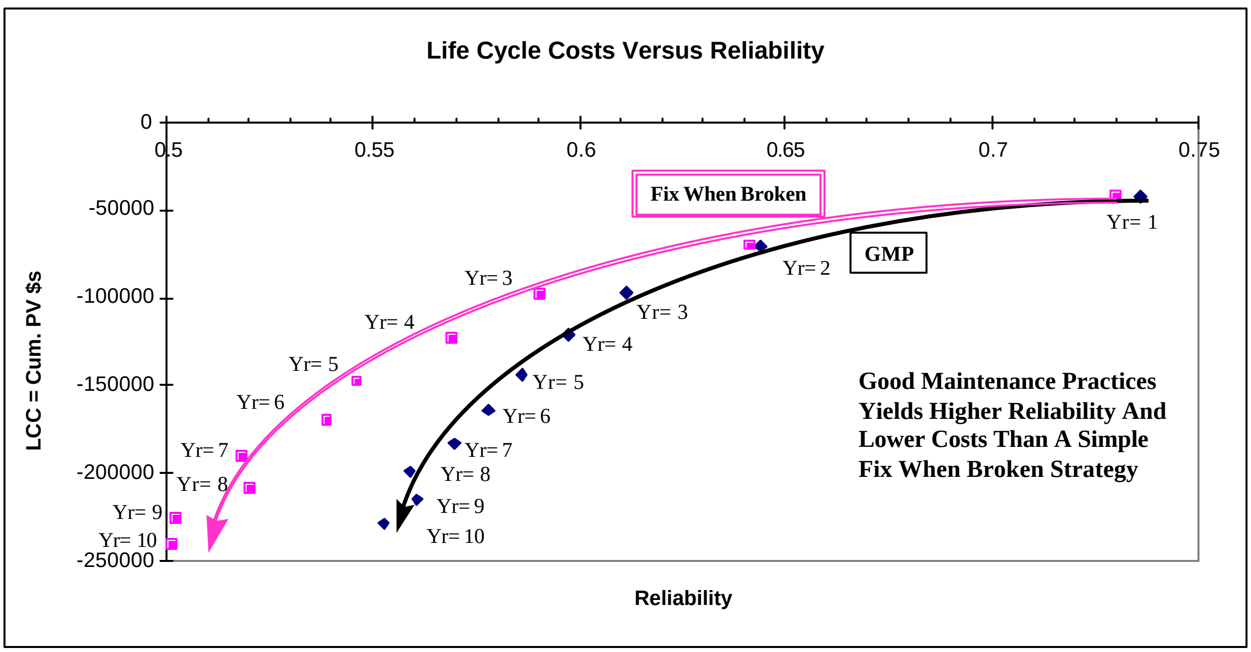


Figure 8: LCC and System Effectiveness

One issue often hidden, but clearly identified in Figures 6 and 7, is 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. Choosing high efficiency internals for the pumps can save another 5-10% of the total power cost. In short, purchase high efficiency motors and high efficiency pump internals carefully matched to the task can 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. The LCC point is this: examining cost reduction possibilities by use of cost details can be productive for discovering real savings opportunities.

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

Figures 6 and 7 show two out of three vital elements are associated with failures of seals and bearings (remember the failure costs are driven by gross margin losses associated with the failures), while the third item is the high cost of electrical power. The real issue here is to conserve NPV values but the old nemesis of maintenance costs always raises its head.

One gnawing problem is: What are the costs if lost gross margins are not included so that true maintenance costs are highlighted? Avoiding loss of gross margins is often accomplished by use of redundant equipment. Setting gross margin losses to zero in Table 1 and Table 7, produces different costs. Then lesser motivation exists for reducing the number of failures—thus fix when broken becomes a very slightly better strategy as failures are not penalized by the loss of gross margin.

Step 11: Select preferred course of action using LCC.

Purchase pumping equipment which is electrical power efficient and correctly sized with high hydraulic efficiency to make substantial reductions in electrical power consumption. The electrical costs are usually a hidden cost item but clearly identified by LCC as a vital element. Use good maintenance practices to reduce failure costs and to provide more reliable equipment.

SUMMARY

Life cycle costs include cradle-to-grave costs. LCC provides the tools to engineer maintenance budgets and 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 as a percentage of installed capital.

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.

Each example described above can be made more accurate by using more complicated models. For one example, in the Monte Carlo model, repair time can be changed from a fixed interval to a statistical interval by 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.

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 they're 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 identified. 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.

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10/14/96