

How to Justify Machinery Improvements Using Reliability Engineering Principles

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Engineering facts, acquisition and installation costs, and operating conditions are merged into a spreadsheet Monte Carlo model to observe life, death, and replacement of pumping equipment using reliability engineering principles. The analysis shows how to select cost-effective equipment from alternatives using

net present value to put engineering details into terms the accounting community understands and trade-offs are explained to justify engineering practices.

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ABSTRACT

For the typical machinery engineer, the difficulties encountered with making reliability improvements lie not with the "mechanics" of improvements, but with justifying the cost of improvements. It's difficult to translate sound engineering principles into terms that the accounting community can understand.

The purpose of this paper is to equip machinery engineers with reliability engineering principles that translate "best practices" into net present value financial terms. Using the concepts of life cycle costs, the effects of off-design conditions and poor installation practices will be shown to reduce the expected life of a pump by as much as 60%. A Monte Carlo simulation will be used to compare commercial practices, good practices, and best practices for a specific pump installation. Life cycle costs will be summarized, for each case, in net present value, to select the best equipment choice.

LIFE CYCLE COST INTRODUCTION

Life cycle costs (LCC) sum all total costs from inception to disposal for both equipment and projects (Barringer 1996). 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, the grade of installation and use practices, and maintenance strategies. The typical problem of specifying and justifying equipment is producing the numbers and making them defensible in the face of numerous conflicts:

- Project engineers want to minimize capital expenditures,
- Maintenance Engineers want to minimize repair hours,
- Production wants to maximize uptime hours,
- Reliability Engineers want to maximize equipment reliability, and
- Accounting wants to maximize net present value of the project.

These conflicting issues, with no specific answers, result in a management edict to "buy cheap and complete the project quickly". This paper will show how to find the numbers so an average engineer has a working tool to "buy right rather than buying cheap" and finish the analysis quickly.

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 engineering art and science are merged with good judgment.

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. Remember the adage attributed to John Ruston: "It's unwise to pay too much, but it's foolish to spend too little".

Usually procurement cost is the only value in life cycle cost which is well known and clearly identified—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.

WHAT GOES INTO LIFE CYCLE COSTS?

The basic cost tree for LCC starts simply. The tree has two branches for acquisition costs and sustaining costs as shown in Figure 1.

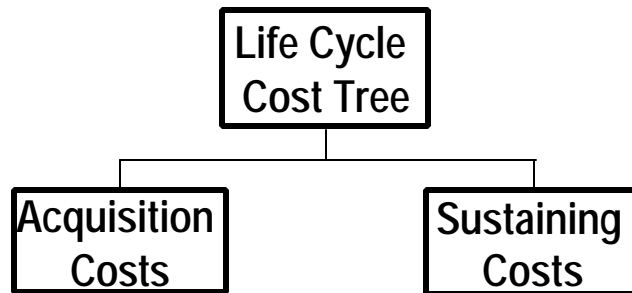


Figure 1: Top Levels Of Life Cycle Cost Tree

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.

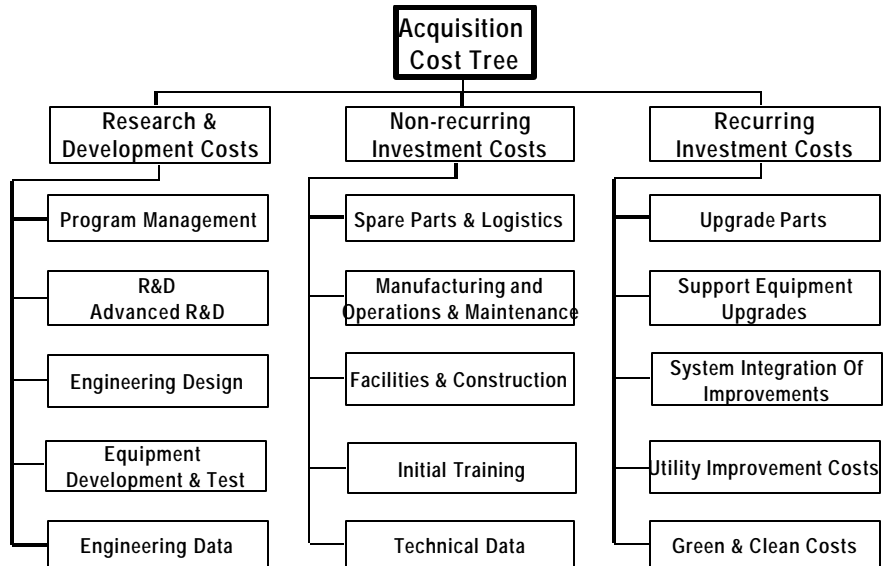


Figure 2: Acquisition Cost Tree

The collection of costs for the sustaining tree shown in Figure 3 is the major problem!

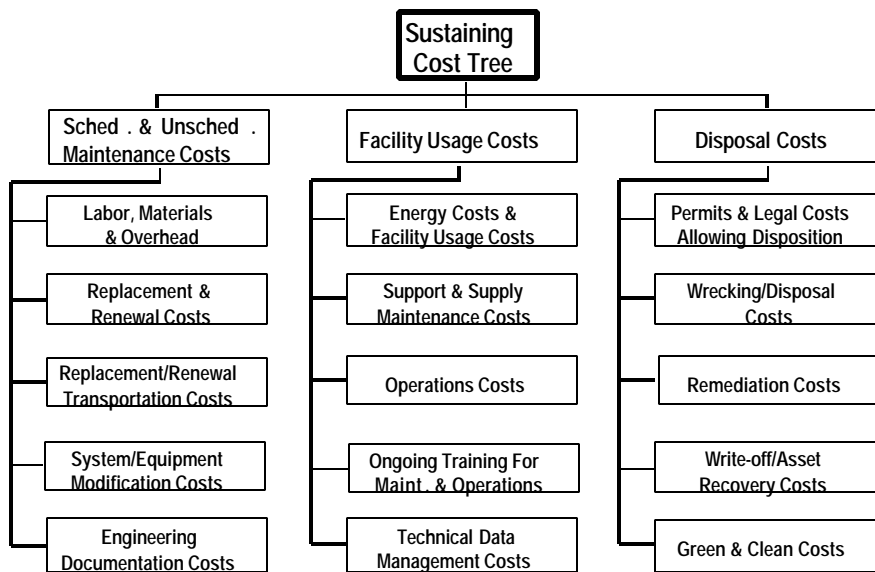


Figure 3: Sustaining Cost Tree

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.

The cost details must go into the correct time buckets to make the life cycle cost information useful. Cost details are important for 1) how much cost, and 2) when costs are incurred. These details are used for calculating net present value. Net present value is the single most important financial indicator for making decisions relating to capital issues.

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

Most capital equipment authorizations ignore major portions of the sustaining cost tree as they lack details for the sustaining 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.

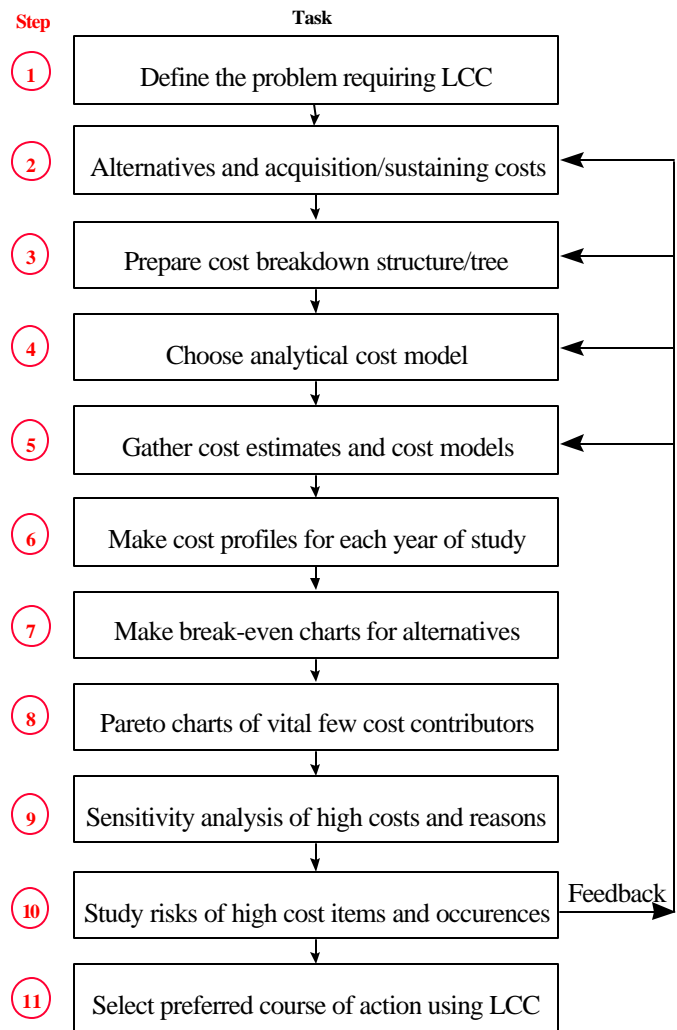


Figure 4: Process Flow For LCC Calculations

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

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.

The process requires installation of a new pump for a forthcoming modification. It is a 30 horse power pump: 3" inlet x 1.5" outlet x 10" volute with an 8" impeller. The pump provides water for transporting 30,000 lb./hr. of high-density polyethylene (HDPE) pellets.

If the pumping system fails, it shuts down the process and penalizes the plant with gross margin losses of \$3,000 per hour of failure.

Step 2: Alternatives and acquisitions/sustaining costs.

Study two grades of pumps: 1) ANSI, and 2) ANSI Enhanced with extra rigid base plate. Note that API pumps are not a consideration because no physical need exists for utilization the high grade features such as high temperature, etc.

Study two physical installation alternates: 1) solo pump, and 2) dual pumps. The dual pumps will be run in sequence of one week on-line and one week off-line.

Study two maintenance strategies: 1) fix when broken, and 2) good maintenance practices of replacing additional components when the pump has failed so that reliability is improved and future failures delayed.

Study three grades of installation and use: 1) commercial installation from quick/cheap installations and widely varying operating conditions, 2) better installation and use practices with reasonable limits imposed, and 3) best installation and best use practices imposed for precise installation and small variations allowed during operation of the equipment. Of course each grade of installation/use is increasingly more expensive to implement and control.

The study options and conditions listed above require solving 24 separate problems as shown in Table 1.

Solve Problems For:						
Net Present Value, Availability, Reliability, Effectiveness, and Maintenance Hours						
	Fix When Broken Maintenance			Good Maintenance Practices		
	Installation/Use Practices			Installation/Use Practices		
ANSI Pump	Commercial	Better	Best	Commercial	Better	Best
Solo NPV	\$	\$	\$	\$	\$	\$
Solo R*A	%	%	%	%	%	%
Maintenance Downtime	hrs.	hrs.	hrs.	hrs.	hrs.	hrs.
Dual NPV	\$	\$	\$	\$	\$	\$
Dual R*A	%	%	%	%	%	%
Maintenance Downtime	hrs.	hrs.	hrs.	hrs.	hrs.	hrs.
ANSI Enhanced Pump						
Solo NPV	\$	\$	\$	\$	\$	\$
Solo R*A	%	%	%	%	%	%
Maintenance Downtime	hrs.	hrs.	hrs.	hrs.	hrs.	hrs.
Dual NPV	\$	\$	\$	\$	\$	\$
Dual R*A	%	%	%	%	%	%
Maintenance Downtime	hrs.	hrs.	hrs.	hrs.	hrs.	hrs.

Table 1: Solve 24 Problems To Find The Best Solution

Step 3: Prepare cost breakdown structure/tree. Each case for the cost breakdown structure will incur cost in these categories of Figure 5. This is a check list for cost to be collected

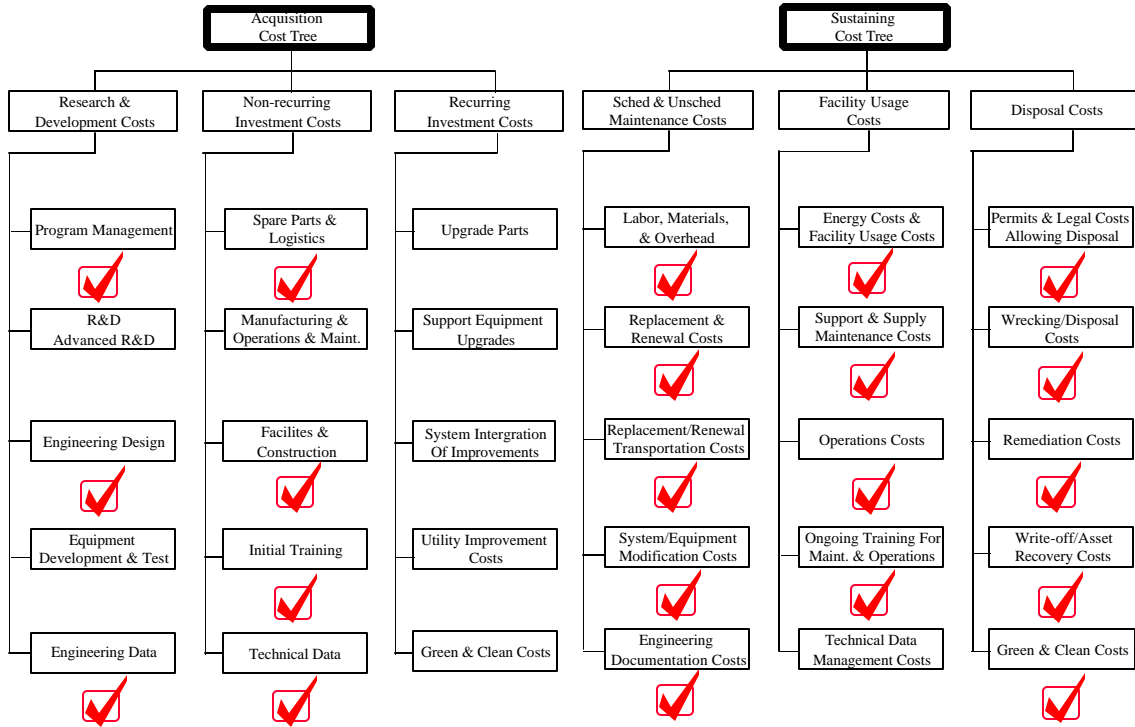


Figure 5: Cost Components For Each Grade Of Pump

Note for this analysis, the obvious costs which are generally defined correctly in most projects for the acquisition costs such as project management costs, etc. **are not** included because they are common to all

	ANSI			ANSI Enhanced		
	Commercial Practices Installation & Use	Better Practices Installation & Use	Best Practices Installation & Use	Commercial Practices Installation & Use	Better Practices Installation & Use	Best Practices Installation & Use
Base Purchase Price	\$ 5,711	\$ 5,711	\$ 5,711	\$ 9,050	\$ 9,050	\$ 9,050
Factory balance	\$ -	\$ 75	\$ 150	\$ -	\$ 75	\$ 150
Field align rotating components	\$ 150	\$ 180	\$ 225	\$ 150	\$ 180	\$ 225
Foundations	\$ 500	\$ 1,000	\$ 1,500	\$ 833	\$ 1,650	\$ 2,500
Mount pump to foundation	\$ 400	\$ 600	\$ 800	\$ 400	\$ 600	\$ 800
Grout	\$ 250	\$ 500	\$ 750	\$ 250	\$ 500	\$ 750
Valves/fitings	\$ 750	\$ 825	\$ 1,000	\$ 750	\$ 825	\$ 1,000
Straight run of pipe	\$ 100	\$ 120	\$ 130	\$ 100	\$ 120	\$ 130
Assembly of piping system	\$ 500	\$ 625	\$ 750	\$ 500	\$ 625	\$ 750
Field align piping systems	\$ 100	\$ 150	\$ 200	\$ 100	\$ 150	\$ 200
Electrical	\$ 2,000	\$ 2,000	\$ 2,000	\$ 2,000	\$ 2,000	\$ 2,000
Instrumentation	\$ 500	\$ 500	\$ 500	\$ 500	\$ 500	\$ 500
Modify Impeller For BEP	\$ -	\$ 125	\$ 150	\$ -	\$ 125	\$ 150
High efficiency motor	\$ 1,318	\$ 1,318	\$ 1,318	\$ 1,318	\$ 1,318	\$ 1,318
Total =	\$ 12,279	\$ 13,729	\$ 15,184	\$ 15,951	\$ 17,718	\$ 19,523

Table 2: Capital Costs Details

of the cases. This analysis pays particular attention to the sustaining cost tree items.

Capital costs for the acquisition trees are shown in Table 2. The costs in Table 2 are for solo pump configuration and dual pumps will double these acquisition costs.

	ANSI				ANSI Enhanced			
	Item Cost	Logistic Cost	Labor + Expense	Total	Item Cost	Logistic Cost	Labor + Expense	Total
Impeller	\$ 700	\$ 300	\$ 800	\$ 1,800	\$ 700	\$ 300	\$ 800	\$ 1,800
Housing	\$ 500	\$ 300	\$ 1,000	\$ 1,800	\$ 500	\$ 300	\$ 1,000	\$ 1,800
Pump Bearings	\$ 175	\$ 75	\$ 800	\$ 1,050	\$ 300	\$ 75	\$ 800	\$ 1,175
Mech. Seal	\$ 350	\$ 100	\$ 800	\$ 1,250	\$ 1,000	\$ 100	\$ 800	\$ 1,900
Bearing Seal	\$ 50	\$ 75	\$ 800	\$ 925	\$ 300	\$ 75	\$ 800	\$ 1,175
Shaft	\$ 350	\$ 300	\$ 800	\$ 1,450	\$ 350	\$ 300	\$ 800	\$ 1,450
Coupling	\$ 100	\$ 75	\$ 800	\$ 975	\$ 700	\$ 75	\$ 800	\$ 1,575
Motor Bearings	\$ 150	\$ 200	\$ 800	\$ 1,150	\$ 150	\$ 200	\$ 800	\$ 1,150
Replacement Mtr.	\$ 1,000	\$ 200	\$ 800	\$ 2,000	\$ 1,000	\$ 200	\$ 800	\$ 2,000
Motor Starter	\$ 500	\$ 75	\$ 100	\$ 675	\$ 500	\$ 75	\$ 100	\$ 675

Table 3: Item Replacement Costs

Elapsed Repair Time (hours)

	ANSI	ANSI Enhanced
Impeller	6	7
Housing	12	13
Pump Bearings	6	7
Mechanical Seal	6	7
Bearing Seal	8	9
Shaft	6	7
Coupling	6	7
Motor Bearings	6	7
Replacement Motor	6	7
Motor Starter	1	1

Table 4: Replacement Times--hours

Replacement costs for the sustaining tree concerning each item are shown in Table 3.

Time required for making replacements for the sustaining tree is shown in Table 4.

Time required for good maintenance practices are paced by the item that fails, and assume all other

	Solo Pump	Dual Pump
Probability of system failure	100%	0.1%
\$/hr Consequences if failure occurs	\$ 3,000	\$ 3,000
\$/hr Risks	\$ 3,000	\$ 3

Probability of simultaneous failure of dual pumps = $P_p * U_A$
 where: P_p = probability of primary device failure in one year
 U_A = unavailability of the standby device in one year

Table 5: Risk Costs For System Failure--Solo And Dual Pumps

replacements are accomplished within the allotted time for repair of the failure.

System failure costs for the sustaining tree concerning solo and dual pumps are shown in Table 5:

Pump performance details and electrical costs for the sustaining tree are summarized in Table 6:

	Commercial 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%
Pump efficiency at lowest allowed flow	52%	54%	55%
Pump efficiency at BEP	55%	55%	55%
Pump efficiency at highest allowed flow	55%	55%	55%
Lowest allowed flow (gpm)	140	160	180
Flow at BEP (gpm)	200	200	200
Highest allowed flow (gpm)	230	220	210
Total head at lowest allowed flow (ft)	285	278	270
Total head at BEP (ft)	260	260	260
Total head at highest allowed flow (ft)	240	245	250
Specific gravity of fluid	1	1	1
Horsepower for lowest allowed flow (hp)	19.38	20.99	22.31
Horsepower for BEP (hp)	23.88	23.88	23.88
Horsepower for highest allowed flow (hp)	25.34	24.75	24.10
Installed Motor Horsepower	30	30	30
Motor Efficiency	95%	98%	98%
Electrical cost \$(/yr-hp)	\$ 350	\$ 350	\$ 350
Electrical costs per year @ installed hp (\$/yr)	\$ 11,053	\$ 8,527	\$ 8,527
Percent Of Time System Is Operating	100%	100%	100%

Table 6: Pump Performance Details And Electrical Costs

Details in Tables 2 through 6 provide cost information. They lack cost profiles in discrete time intervals for the sustaining cost tree which will be used in NPV calculations.

Reliability models are needed to find when end of component life occurs as costly replacements follow death of the component. Details from the reliability models go into the sustaining costs.

Every piece of equipment is comprised of components. Each component has an inherent reliability. Inherent (or intrinsic reliability) is the best theoretical capability of components that can be demonstrated in a laboratory environment.

Inherent component reliability is altered downward, as measured by age-to-failure, by grade of installation and how the equipment is used. 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. LCC accuracy improves and benefits from quantification of grade issues just as LCC analysis improves by used of probabilistic analysis rather than deterministic analysis. Most engineers know that nothing dies on schedule and nothing gets repaired on schedule--the problem is how to quantify the details.

Very high-grade installations and very high-grade practices for operation of the equipment demonstrate (by long ages-to-failure) most of the inherent equipment life is usable. However, low-grade installations and

low-grade operations destroy inherent life of equipment. The key for LCC calculations is accurately reflection of effects of practices on inherent reliability. This is frequently accomplished by laboratory tests on low-cost electronic components but seldom quantified on high- priced mechanical components. Thus the effects of practices on inherent life must be obtained by surveys from experts in the field. Field surveys may not be the desired method of acquiring data but it is the most practical method considering time and costs--this forms the art of engineering which is used with the science of engineering to derive practical answers in real time.

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

Maintenance departments and operation departments, 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 lack details for quantifying their opinions.

Good LCC analysis responds to accusations of detractors by providing monetary results to refute charges of gold plating, over design, high cost, and other overstatements/exaggerations. The resulting life multipliers from Table 7 alter the inherent reliability of equipment and change base failure rates (lower failure rates) to predict actual failure rates (higher failure rates).

		Pump Curve % Off BEP	L/D Suction Straight Runs	Rotational Shaft Alignment	Piping Alignment	Rotational Balance	Foundation Design	Grouting
Best Practices	Resulting eta 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%
Mech. Seal	0.9533	98%	99%	100%	100%	100%	100%	100%
Bearing Seal	0.8719	98%	99%	100%	100%	100%	100%	100%
Shaft	0.9801	98%	100%	100%	100%	99%	100%	100%
Coupling	1.0000	99%	100%	99%	100%	100%	100%	100%
Motor Bearings	1.0000	100%	100%	100%	100%	100%	100%	100%
Replacement Mtr.	1.0000	99%	100%	99%	100%	100%	100%	100%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%
Better Practices	Resulting eta 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%
Mech. Seal	0.4314	88%	90%	90%	84%	90%	90%	90%
Bearing Seal	0.3950	88%	90%	90%	84%	90%	90%	90%
Shaft	0.5705	79%	90%	88%	88%	90%	90%	90%
Coupling	0.6036	92%	95%	90%	94%	95%	90%	91%
Motor Bearings	0.9776	94%	93%	94%	97%	95%	90%	90%
Replacement Mtr.	0.6036	100%	100%	100%	100%	100%	99%	99%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%
Commercial Practices	Resulting eta 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	Cementitious & 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%
Mech. Seal	0.0095	65%	60%	58%	40%	61%	50%	55%
Bearing Seal	0.0151	51%	60%	40%	40%	64%	55%	55%
Shaft	0.1149	65%	60%	58%	40%	61%	50%	55%
Coupling	0.0737	76%	80%	65%	71%	78%	70%	75%
Motor Bearings	0.8625	78%	80%	55%	80%	75%	60%	60%
Replacement Mtr.	0.0737	100%	100%	100%	100%	100%	100%	100%
Motor Starter	1.0000	100%	100%	100%	100%	100%	100%	100%

Table 7: Centrifugal Pump Practices, Life, And Costs

The multipliers from Table 7 are used in Table 8 to alter the inherent reliability model. Notice how the ANSI model and the ANSI Enhanced models have different inherent life. For the best practices, only 3% of the inherent life is lost compared to 44% loss of life for better practices and 97% loss of inherent life for

Inherent Component Reliability	30 hp pump: 3"x1.5"x10" with 8" impeller pellet water pump for a 30,000 lb./hr. HDPE unit			Best Practices Installation & Use	Effects Of Practices on Component Life		MTTF (yrs)= $h \cdot G(1 + 1/b)$		
	beta	eta	MTTF (yrs)= $h \cdot G(1 + 1/b)$		Multiplier	beta			eta
	shape factor (no dimensions)	location factor (hrs)			Eta Life Multiplier From Practices	shape factor (no dimensions)			location factor (hrs)
Impeller	2.5	300,000	30.39	0.9726	2.50	291,784	29.55	MTBF For All Mech.--> 2.00 Items For All Elect.--> 6.41 Items	
Housing	1.3	300,000	31.63	0.8547	1.30	256,412	27.03		
Pump Bearings	1.3	100,000	10.54	0.9712	1.30	97,119	10.24		
Mech. Seal	1.4	150,000	15.61	0.9677	1.40	145,159	15.10		
Bearing Seal	1.4	75,000	7.80	0.9677	1.40	72,579	7.55		
Shaft	1.2	300,000	32.21	0.9712	1.20	291,357	31.29		
Coupling	2	100,000	10.12	0.9801	2.00	98,010	9.92		
Motor Bearings	1.3	150,000	15.81	1.0000	1.30	150,000	15.81		
Replacement Mtr.	1.1	150,000	16.52	0.9801	1.10	147,015	16.19		
Motor Starter	1.2	300,000	32.21	1.0000	1.20	300,000	32.21		
			1.57	--Mean time between system failures=		1.52			
			13,767 hours	D = Loss	3%	or=	13,354 hours	loss=	
							413 hours		

Inherent Component Reliability	30 hp pump: 3"x1.5"x10" with 8" impeller pellet water pump for a 30,000 lb./hr. HDPE unit			Best Practices Installation & Use	Effects Of Practices on Component Life		MTTF (yrs)= $h \cdot G(1 + 1/b)$		
	beta	eta	MTTF (yrs)= $h \cdot G(1 + 1/b)$		Multiplier	beta			eta
	shape factor (no dimensions)	location factor (hrs)			Life Multiplier * eta From Practices	shape factor (no dimensions)			location factor (hrs)
Impeller	2.5	300,000	30.39	0.9726	2.50	291,784	29.55	MTBF For All Mech.--> 4.19 Items For All Elect.--> 6.41 Items	
Housing	1.3	300,000	31.63	0.8547	1.30	256,412	27.03		
Pump Bearings	1.3	300,000	31.63	0.9712	1.30	291,357	30.72		
Mech. Seal	1.4	200,000	20.81	0.9677	1.40	193,545	20.14		
Bearing Seal	1.4	500,000	52.02	0.9677	1.40	483,863	50.34		
Shaft	1.2	300,000	32.21	0.9712	1.20	291,357	31.29		
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		
Replacement Mtr.	1.1	150,000	16.52	0.9801	1.10	147,015	16.19		
Motor Starter	1.2	300,000	32.21	1.0000	1.20	300,000	32.21		
			2.62	--Mean time between system failures=		2.53			
			22,919 hours	D = Loss	3%	or=	22,205 hours	loss=	
							715 hours		

Table 8: Reliability Model Altered By Effects Of Practices

the lowest grade commercial practices.

Table 8 also shows taxonomy (the classification of equipment in a ordered system that indicates natural relationships) effects on life. Life of the mechanical portion of the system is different than for the electrical system. When both are considered together, system life is much shorter. The taxonomy definitions demonstrate why different organizations talk about different numbers for the same device. Reciprocals of the MTTF in Table 8 give failure rates, which could be used for deterministic computations of NPV--deterministic NPV calculations are simpler but often give inaccurate results when components have wear-out failure modes as shown above.

Table 8 uses Weibull statistics to characterize component life (Abernethy 1998). Weibull descriptors are tools of choice for reliability engineers. Beta value implies failure modes for the components. In Table 8, the beta values are greater than unity and imply wear-out failure modes.

Good Maintenance Practices To Fix Each Component When Broken Strategy Plus Other Associated Components											Ledgend
	Impeller	Housing	Pump Bearings	Mech. Seal	Bearing Seal	Shaft	Coupling	Motor Bearings	Replacem ent Mtr.	Motor Starter	Impeller
Impeller	1	0	0	0	0	0	0	0	0	0	1
Housing	0	1	0	0	0	0	0	0	0	0	0
Pump Bearings	1	1	1	1	1	0	0	0	0	0	1
Mech. Seal	1	1	1	1	1	0	0	0	0	0	1
Bearing Seal	0	0	0	0	1	0	0	0	0	0	0
Shaft	0	0	0	0	0	1	0	0	0	0	0
Coupling	0	0	0	0	0	0	1	1	1	0	0
Motor Bearings	0	0	0	0	0	0	0	1	0	0	0
Replacement Mt	0	0	0	0	0	0	0	0	1	0	0
Motor Starter	0	0	0	0	0	0	0	0	0	1	0

Fix When Broken Strategy: 1=Replace, 0=Do Not Replace										
	Impeller	Housing	Pump Bearings	Mech. Seal	Bearing Seal	Shaft	Coupling	Motor Bearings	Replacem ent Mtr.	Motor Starter
Impeller	1	0	0	0	0	0	0	0	0	0
Housing	0	1	0	0	0	0	0	0	0	0
Pump Bearings	0	0	1	0	0	0	0	0	0	0
Mech. Seal	0	0	0	1	0	0	0	0	0	0
Bearing Seal	0	0	0	0	1	0	0	0	0	0
Shaft	0	0	0	0	0	1	0	0	0	0
Coupling	0	0	0	0	0	0	1	0	0	0
Motor Bearings	0	0	0	0	0	0	0	1	0	0
Replacement Mt	0	0	0	0	0	0	0	0	1	0
Motor Starter	0	0	0	0	0	0	0	0	0	1

Ledgend

1
0
1
1

When Impeller fails-- replace bearings and seal

Table 9: Maintenance Replacement Strategies

The cost data above must also include maintenance replacement strategies as shown in Table 9.

With the input data from Tables 2-9, the search can begin for minimizing the lowest long-term cost of ownership as found by LCC. Every LCC 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.

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 Monte Carlo simulation is performed using an Excel spreadsheet--every solution gives different answers.

Monte Carlo models use random numbers to simulate the probability of failure. This in turn is used to calculate the age to failure for each component. The age to failure (t) for each component in Table 8 is driven by the Weibull equation. The characteristic age at failure, eta, and the Weibull shape factor, beta, are found from actual or hypothesized ages to failure and in turn describe the cumulative distribution function (CDF) which is a statistical term. The CDF varies from 0 (no deaths) to 1 (all are dead), and the characteristic life, eta, occurs when the CDF = 63.2%..

The Weibull equation, written in-age-to-failure, is $t = \eta * (\ln(1/(1-CDF)))^{1/\beta}$. Fortunately, Excel has a random number function, RAND() , which produces numbers between 0 and 1. The random number generator simplifies calculations by substituting RAND() for the CDF values.

Here is an example of how the Weibull equation will work in the Monte Carlo model. Find the age to failure in Table 7 for an ANSI pump seal where $\beta = 1.4$, $\eta = 150,000$ hours using a random number of 0.303: thus, $t = 150000 * (\ln(1/(1-0.303)))^{1/1.4} = 72,443$ hours Each time a new random number is selected, the age to failure will be different but driven by the statistical parameters β and η which characterize the ages to failure for the component. This method represents the real life situation as you never know how long a specific component will last! The Monte Carlo model starts with an initial complement of equipment who's life is randomly selected for each component, and the model will wind-down the simulated life numbers until end of useful life occurs.

Summary		Failure Rate and Cost Summary By Year--Dual ANSI, Best Installation and Use, Good Maintenance Practices										
1000 <--# Iteration		1	2	3	4	5	6	7	8	9	10	
Average Of Cumulative Failures Per Year	Impeller	0.000	0.000	0.002	0.003	0.002	0.003	0.007	0.007	0.013	0.012	
	Housing	0.006	0.008	0.025	0.032	0.023	0.023	0.029	0.028	0.027	0.020	
	Pump Bearings	0.006	0.008	0.025	0.032	0.023	0.023	0.029	0.028	0.027	0.020	
	Mech. Seal	0.025	0.030	0.038	0.038	0.033	0.036	0.048	0.048	0.033	0.032	
	Bearing Seal	0.049	0.072	0.090	0.105	0.137	0.116	0.112	0.135	0.115	0.120	
	Shaft	0.020	0.016	0.014	0.017	0.020	0.030	0.020	0.024	0.030	0.026	
	Coupling	0.004	0.034	0.040	0.034	0.045	0.052	0.071	0.062	0.067	0.076	
	Motor Bearings	0.028	0.034	0.044	0.057	0.054	0.049	0.067	0.049	0.063	0.059	
	Replacement Mtr.	0.046	0.049	0.066	0.058	0.058	0.051	0.065	0.063	0.052	0.052	
	Motor Starter	0.018	0.017	0.026	0.023	0.025	0.031	0.018	0.023	0.031	0.030	
	Totals	0.202	0.268	0.370	0.399	0.420	0.414	0.466	0.467	0.458	0.447	
	Mt'ce Down Hrs	1.256	1.715	2.420	2.681	2.807	2.699	3.104	3.125	2.985	2.892	
	Average Of Cumulative Suspensions Per Year	Impeller	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Housing	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pump Bearings		0.080	0.110	0.155	0.178	0.195	0.178	0.196	0.218	0.188	0.184	
Mech. Seal		0.090	0.148	0.173	0.206	0.227	0.206	0.246	0.224	0.223	0.212	
Bearing Seal		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Shaft		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Coupling		0.074	0.083	0.110	0.115	0.112	0.100	0.132	0.112	0.115	0.111	
Motor Bearings		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Replacement Mtr.		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	
Totals		0.244	0.341	0.438	0.499	0.534	0.484	0.574	0.554	0.526	0.507	
Average Of Cumulative Costs Per Year		Impeller	\$ -	\$ -	\$ 4	\$ 5	\$ 4	\$ 5	\$ 13	\$ 13	\$ 24	\$ 22
		Housing	\$ 11	\$ 15	\$ 46	\$ 59	\$ 42	\$ 42	\$ 53	\$ 51	\$ 50	\$ 37
		Pump Bearings	\$ 57	\$ 100	\$ 99	\$ 115	\$ 118	\$ 113	\$ 154	\$ 112	\$ 120	\$ 110
	Mech. Seal	\$ 72	\$ 105	\$ 126	\$ 141	\$ 144	\$ 138	\$ 172	\$ 162	\$ 142	\$ 136	
	Bearing Seal	\$ 47	\$ 68	\$ 85	\$ 100	\$ 130	\$ 110	\$ 106	\$ 128	\$ 109	\$ 114	
	Shaft	\$ 29	\$ 23	\$ 21	\$ 25	\$ 29	\$ 44	\$ 29	\$ 35	\$ 44	\$ 38	
	Coupling	\$ 17	\$ 48	\$ 59	\$ 54	\$ 64	\$ 69	\$ 94	\$ 81	\$ 87	\$ 95	
	Motor Bearings	\$ 33	\$ 40	\$ 51	\$ 67	\$ 63	\$ 57	\$ 78	\$ 57	\$ 74	\$ 69	
	Replacement Mtr.	\$ 93	\$ 99	\$ 133	\$ 117	\$ 117	\$ 103	\$ 131	\$ 127	\$ 105	\$ 105	
	Motor Starter	\$ 12	\$ 12	\$ 18	\$ 16	\$ 17	\$ 21	\$ 12	\$ 16	\$ 21	\$ 20	
	Failure Cost \$	\$ 371	\$ 510	\$ 641	\$ 698	\$ 729	\$ 703	\$ 842	\$ 782	\$ 774	\$ 746	
	Power Cost \$	\$ 8,406	\$ 8,417	\$ 8,402	\$ 8,401	\$ 8,412	\$ 8,411	\$ 8,399	\$ 8,399	\$ 8,415	\$ 8,408	
	Grand Total Cost \$	\$ 8,777	\$ 8,926	\$ 9,043	\$ 9,099	\$ 9,141	\$ 9,114	\$ 9,241	\$ 9,181	\$ 9,189	\$ 9,154	
	1 Yr. Reliability	81.71%	76.49%	69.07%	67.10%	65.70%	66.10%	62.75%	62.69%	63.25%	63.95%	
1 Yr. Availability	99.99%	99.98%	99.97%	99.97%	99.97%	99.97%	99.96%	99.96%	99.97%	99.97%		
Mt'ce Down Hrs	1.256	1.715	2.420	2.681	2.807	2.699	3.104	3.125	2.985	2.892		

Table 10: Monte Carlo Failure Rates and Cost Profiles By Year

Table 10 shows an example of the Monte Carlo results for the first 10 years of life. Notice how the failure rates change by year and other useful information provided in the spreadsheet model.

As an alternative to Monte Carlo solutions, the simple case of using a constant failure rate for each component makes cost calculations easy, for a first cut. However, constant failure rates lack NPV accuracy because NPV calculations are sensitive to what year the failures occur. Higher penalties are

incurred for early failures and advantages go to later failures with delayed costs. Constant failure rates dismiss the advantages of when failures occur.

For the purpose of this paper only, many of the cost items identified above in Figure 2 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 authorization for expenditure (AFE) submissions.

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 Table 8. Alter the life by the factors in Table 7 for three different installation/use practices.

Allow installation of a solo pump or a dual pump with the risk cost consequences of failure as described in Table 5.

Use two maintenance practices of fix when broken or good maintenance practices as described in Table 9.

Draw maintenance costs from Table 3 for the ANSI pump. Use capital costs from Table 2 for the ANSI pump.

Use power consumption costs from Table 6 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 (no profits) are considered, the NPV with the least negative number is the initial winner. This information will complete the top half of Table 1.

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. This will be described later.

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

Same as for alternative #1 but using ANSI enhanced details. The NPV details will complete the bottom half of Table 1

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. Table 10 gives spreadsheet details of the Monte Carlo simulation by year for only a portion of the 20-year study cycle. Each iteration is a 20-year "snapshot" of the birth and death of components. Many iterations are required to obtain a consistent result (1000 iterations). Table 10 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 even though availability remains high.

The grand total of costs in Table 10 is replicated five times and averaged to reduce the errors that randomly occur and with replication and estimate is available for the error in the results. Averaged costs for each period go into the net present value calculation. Table 10 shows power costs are 92%

of total cost in the early years and power as a percentage of total costs declines to 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.

Since the pump in Table 10 is a dual pump and the availability is reported for a single unit, the system availability must be calculated. Two pumps in parallel with 99.97% availability and short repair times as observed in Table 10 is: $A_o \sim 1 - (1 - 0.9997)^2 \sim 0.999,999,9$. In short, the dual pumping system is highly available as the unavailability for the system is 0.00001%!

The probability of system failure in Table 10 for year 5 can be found from the calculated reliability numbers. Probability of failure for a pump is: $POF \sim 1 - 65.70\% = 0.343$, and the unavailability of a pump is $1 - 99.97\% = 0.0003$. Then, the probability of simultaneous pump failures = $0.343 * 0.0003 = 0.0001$. Thus the consequences of failure shown in Table 5 are too harsh at a penalty at \$3/hour of downtime for this case--but this error is a trivial matter.

Each case described above in step 5 produces a cost profile for each year by means of Monte Carlo simulation. The cost profiles are put into a net present value spreadsheet shown in Table 11--only 10 years

Net Present Value Calculations:													
20 ← Project Life in Years													
Cost Elements	Year →	0	1	2	3	4	5	6	7	8	9	10	11
Capital		\$ 30,363											
Costs		\$ -	\$ 8,893	\$ 8,824	\$ 8,917	\$ 8,968	\$ 9,001	\$ 9,036	\$ 9,066	\$ 9,104	\$ 9,115	\$ 9,147	\$ 9,162
Savings (enter as a positive number)													
Depreciation (straight line)			\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518
Profit b4 Taxes			\$ (10,212)	\$ (10,343)	\$ (10,436)	\$ (10,467)	\$ (10,519)	\$ (10,555)	\$ (10,574)	\$ (10,622)	\$ (10,633)	\$ (10,665)	\$ (10,681)
Tax Provision @ 38% of Pbt			\$ 3,880	\$ 3,930	\$ 3,965	\$ 3,965	\$ 3,987	\$ 4,011	\$ 4,018	\$ 4,036	\$ 4,041	\$ 4,053	\$ 4,059
Net Income			\$ (6,331)	\$ (6,413)	\$ (6,470)	\$ (6,502)	\$ (6,522)	\$ (6,544)	\$ (6,556)	\$ (6,586)	\$ (6,593)	\$ (6,612)	\$ (6,622)
Add Back Depreciation			\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518	\$ 1,518
Cash Flow			\$ (4,813)	\$ (4,894)	\$ (4,951)	\$ (4,983)	\$ (5,004)	\$ (5,026)	\$ (5,037)	\$ (5,057)	\$ (5,074)	\$ (5,094)	\$ (5,104)
Discount Factors @ Rate Above		1.00	0.89	0.80	0.71	0.64	0.57	0.51	0.45	0.40	0.36	0.32	0.29
Present Value		\$ (30,363)	\$ (4,297)	\$ (3,902)	\$ (3,524)	\$ (3,167)	\$ (2,839)	\$ (2,546)	\$ (2,279)	\$ (2,047)	\$ (1,830)	\$ (1,640)	\$ (1,467)
Net Present Value		\$ (67,728)											
Discount Rate =		12%											

Table 11: Cost profiles With Net Present Value Calculations

Monte Carlo Solution Results						
ANSI Pump	Fix When Broken Maintenance			Good Maintenance Practices		
	Commercial	Better	Best	Commercial	Better	Best
Solo NPV	\$ (2,836,915)	\$ (153,350)	\$ (98,949)	\$ (2,562,066)	\$ (144,673)	\$ (96,047)
Solo R*A	0%	39%	62%	0%	42%	64%
Maintenance Time/yr	156 hrs	7 hrs	3 hrs	144 hrs	6 hrs	3 hrs
Dual NPV	\$ (198,187)	\$ (67,901)	\$ (67,728)	\$ (233,641)	\$ (68,913)	\$ (68,225)
Dual R*A	0%	39%	62%	0%	42%	64%
Maintenance Time/yr	156 hrs	7 hrs	3 hrs	144 hrs	6 hrs	3 hrs
ANSI Enhanced Pump						
Solo NPV	\$ (1,230,029)	\$ (109,767)	\$ (82,655)	\$ (1,115,875)	\$ (107,368)	\$ (82,732)
Solo R*A	0%	58%	75%	0%	60%	75%
Maintenance Time/yr	67 hrs	4 hrs	2 hrs	62 hrs	4 hrs	2 hrs
Dual NPV	\$ (142,075)	\$ (72,611)	\$ (74,253)	\$ (162,592)	\$ (72,864)	\$ (74,994)
Dual R*A	0%	58%	75%	0%	60%	75%
Maintenance Time/yr	67 hrs	4 hrs	2 hrs	62 hrs	4 hrs	2 hrs

Table 12: NPV Summary

are show from a 20 year spreadsheet. Table 12 summarizes all NPV cost profiles.

Remember the *most favorable* NPV values in Table 12 are the winner with the *smallest negative values* this is because no profits are considered. The most cost-effective winning combination is ANSI dual pump using best installation/use practices and fix when broken maintenance replacement practices with a NPV = -\$67,728.

Table 12, when viewed only from a financial viewpoint developed by combining financial data, installation practices, use practices, and maintenance practices can answer the questions asked at the beginning:

- **Project engineers want to minimize capital expenditures**,--the least capital cost spent is for a solo ANSI pump with commercial installation practices and this will result in the worst financial results with an NPV=(\$2,836,915)--this is a very bad bargain and is number 24 on the list of alternatives. It is not affordable for achieving the lowest long term cost of ownership!
- **Maintenance Engineers want to minimize repair hours**,--the least maintenance hours are achieved with an ANSI enhanced pump and the NPV =(\$74,253) which is number 7 on the top ten list for NPV.
- **Production wants to maximize uptime hours**, --the maximum uptime hours are achieved with a dual ANSI enhanced pump using good maintenance practices and the NPV=(\$74,994) which is number 8 on the top ten list for NPV.
- **Reliability Engineers want to maximize equipment reliability**,-- the best equipment reliability is achieved with a dual ANSI enhanced pump using good maintenance practices and the NPV=(\$74,994) which is number 8 on the top ten list for NPV, and
- **Accounting wants to maximize net present value of the project**--this is obtained with a dual ANSI pump using best practices and a fix when broken strategy and this is number 1 on the top ten list and the NPV = (\$67,728).

Be careful of over-generalizing results from Table 12-13. Each case has it's own special conditions concerning performance and costs although some tendencies prevail.

In Table 12, the figures for maintenance hours, availability and reliability are averages for the 20-year time period. Availability does not change much during the 20 years. However, substantial changes occur for maintenance downtime hours as shown in Figure 6 and reliability changes substantially as shown in Figure 7--both cases illustrate the case for the top item in Table 13 which is a ranking of the top ten NPV values.

Top Ten Alternatives From Monte Carlo Simulations									
Alternative Rank	Pump Grade	Dual Or Solo	Installation & Use Practice	Maintenance Practice	Capital Cost	NPV	Effectiveness ~ R * A	D% For NPV	D% For NPV
1	ANSI	Dual	Best	Fix When Broken	\$ 30,368	\$ (67,728)	62%	-	-
2	ANSI	Dual	Better	Fix When Broken	\$ 27,458	\$ (67,901)	39%	-0.3%	-36.9%
3	ANSI	Dual	Best	Good Practices	\$ 30,368	\$ (68,225)	64%	-0.7%	4.6%
4	ANSI	Dual	Better	Good Practices	\$ 27,458	\$ (68,913)	42%	-1.7%	-31.0%
5	ANSI +	Dual	Better	Fix When Broken	\$ 35,436	\$ (72,611)	58%	-7.2%	-6.1%
6	ANSI +	Dual	Better	Good Practices	\$ 35,436	\$ (73,864)	60%	-9.1%	-2.3%
7	ANSI +	Dual	Best	Fix When Broken	\$ 39,046	\$ (74,253)	75%	-9.6%	21.2%
8	ANSI +	Dual	Best	Good Practices	\$ 39,046	\$ (74,994)	75%	-10.7%	22.2%
9	ANSI +	Solo	Best	Fix When Broken	\$ 19,523	\$ (82,655)	75%	-22.0%	21.1%
10	ANSI +	Solo	Best	Good Practices	\$ 19,523	\$ (82,732)	75%	-22.2%	22.4%

Table 13: Top Ten Alternatives

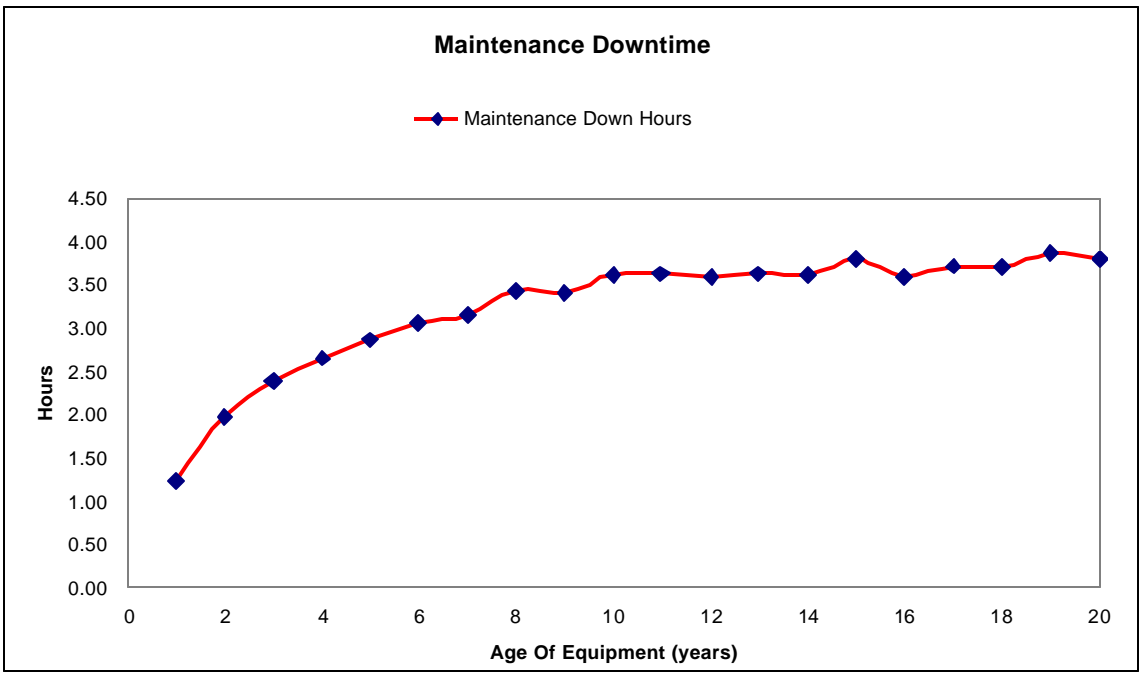


Figure 6: Maintenance Downtime: ANSI, Dual, Best Practices, Fix When Broken

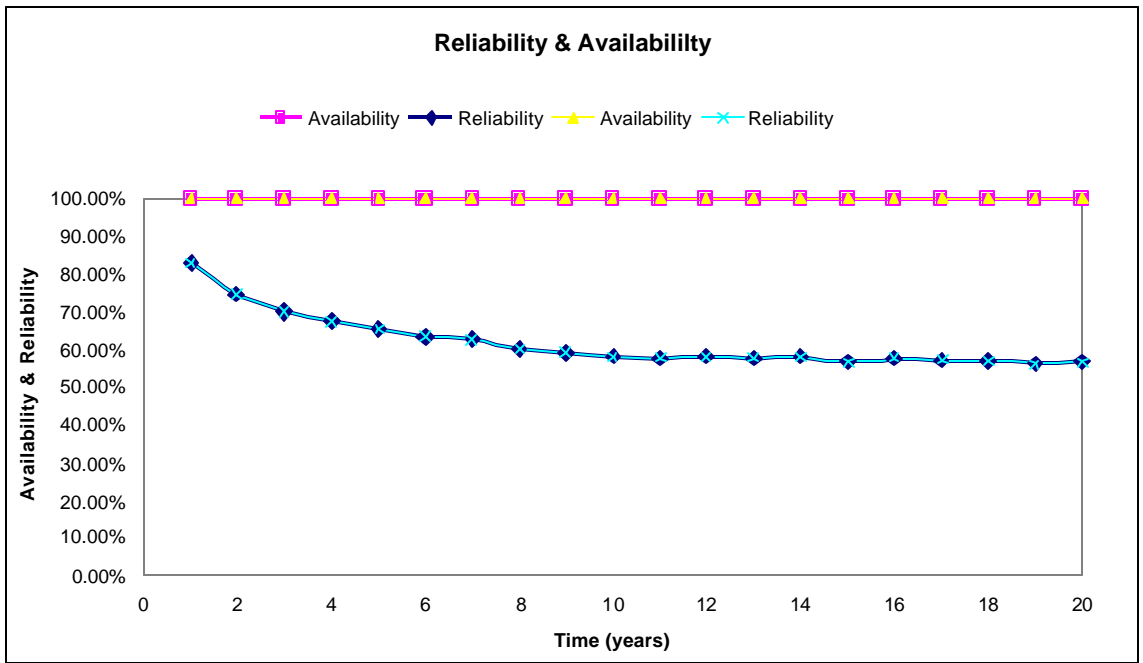


Figure 7: Reliability & Availability: ANSI, Dual, Best Practices, Fix When Broken

Step 7: Make break-even charts for alternatives.

Breakeven charts are generally useful tools for showing a quick grasp of details from the simulations. However Figure 8 does not produce any breakeven choices.

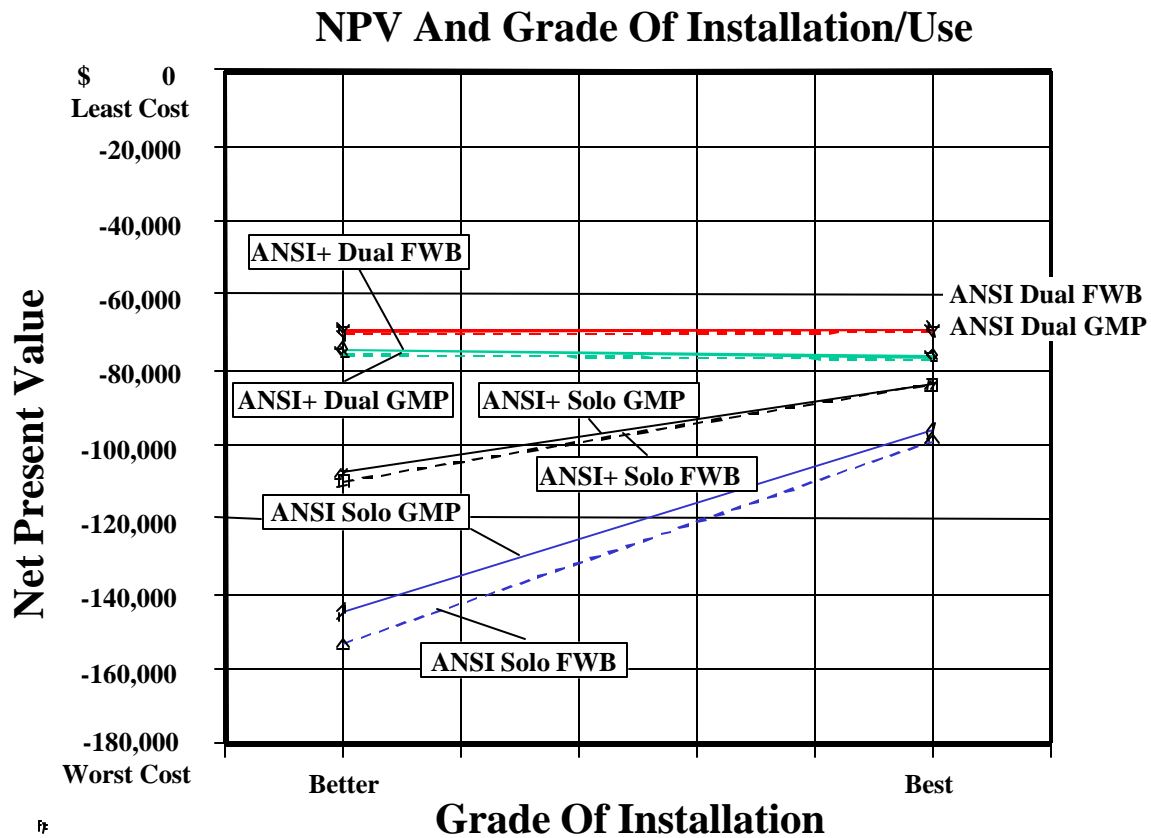


Figure 8: NPV versus Installation /Use Grades

Another technique useful for studying alternatives involves effectiveness. The effectiveness equation is a helpful tool for use as a sales tool for presenting 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:

$$\text{System effectiveness} = \text{Effectiveness/LCC}$$

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:

$$\text{Effectiveness} = \text{availability} * \text{reliability} * \text{maintainability} * \text{capability}$$

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:

$$A = (\text{uptime})/(\text{uptime} + \text{downtime})$$

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 $(\text{uptime} + \text{downtime}) < 8760$ hours per year as the lack of making money is a LCC issue.

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 in simple exponential terms as

$$R(t) = \exp(-t/\text{MTBF}) = \exp(-\lambda t) \text{ or expressed in Weibull terms as } =\exp(-t/\eta)^\beta$$

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.

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

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

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.

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 $0.8 \times 0.8219 = 65.75\%$. 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.

Engineers need graphics to provide a fundamental understanding to the problem. Figure 9 provides a graphical sales tool to display facts for effectiveness and life cycle costs. It helps explain details, and shows why certain actions are preferred. Each engineer wants to select equipment or projects, which have low life cycle costs and high effectiveness--but often this is not accomplished in real life because the ideas are not sold effectively. Figure 9 is a presentation and sales tool using the system effectiveness elements described above.

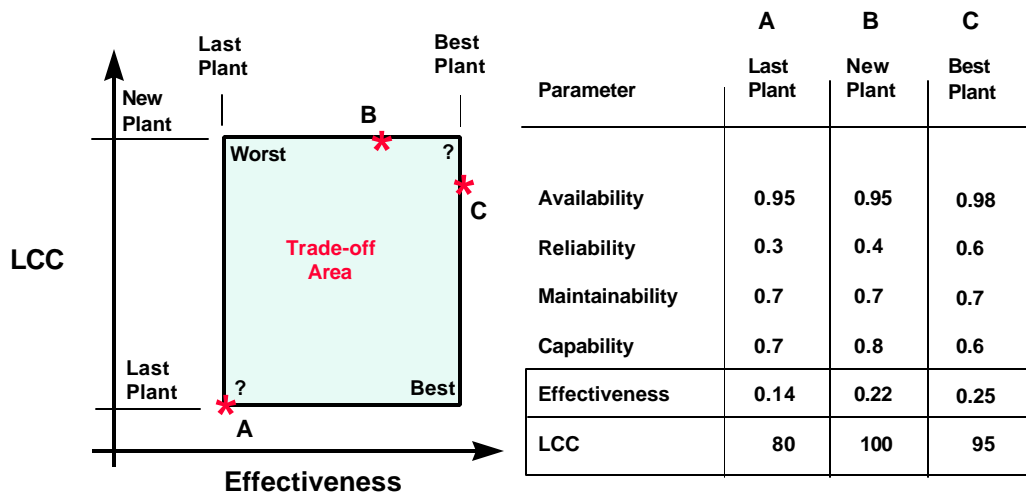


Figure 9: Benchmark Data Shown In Trade-Off Format

The lower right-hand corner of Figure 9 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 10.

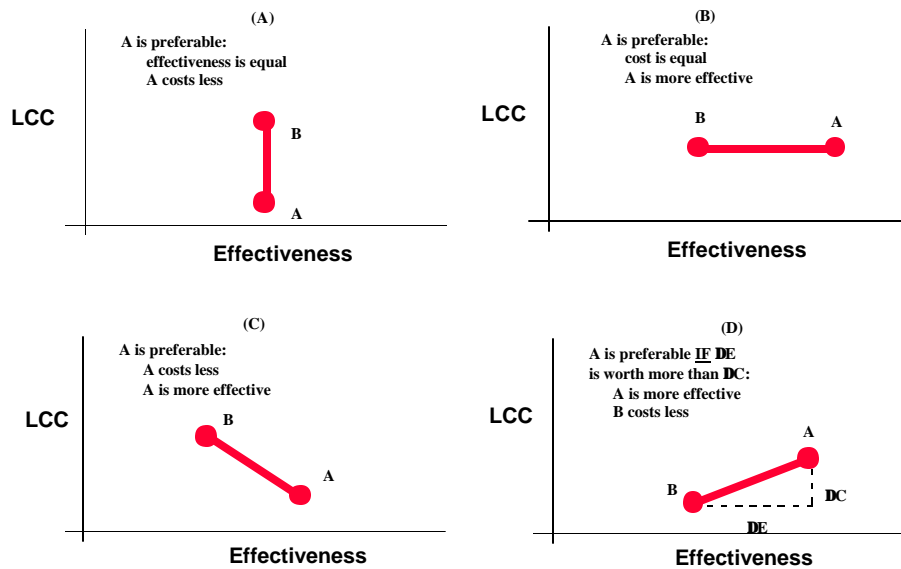


Figure 10: Some Possible Outcomes From Trade-Off Studies

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

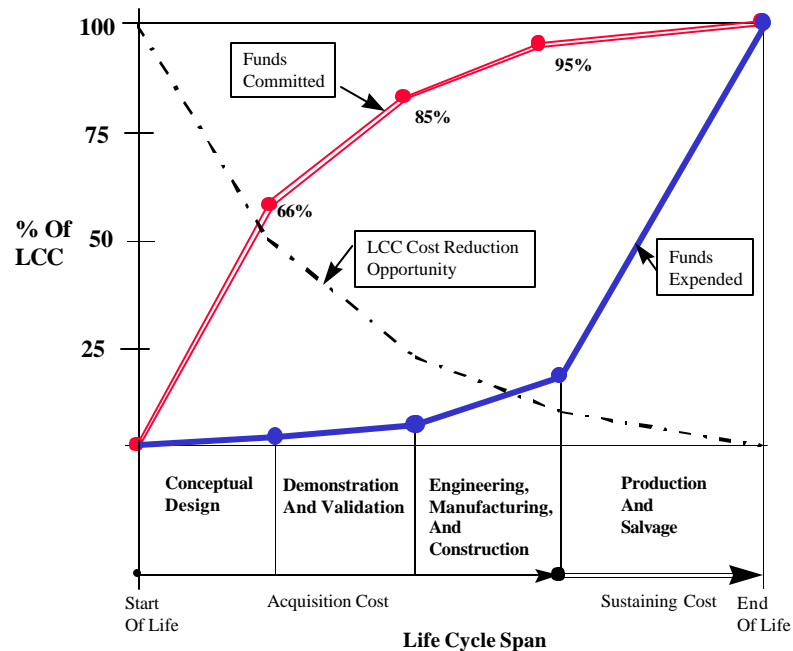


Figure 11: Funding Trends By Commitment And Expenditure

chance to influence LCC cost reductions (Blanchard 1991) grows smaller when projects are converted into bricks and mortar as shown in Figure 11.

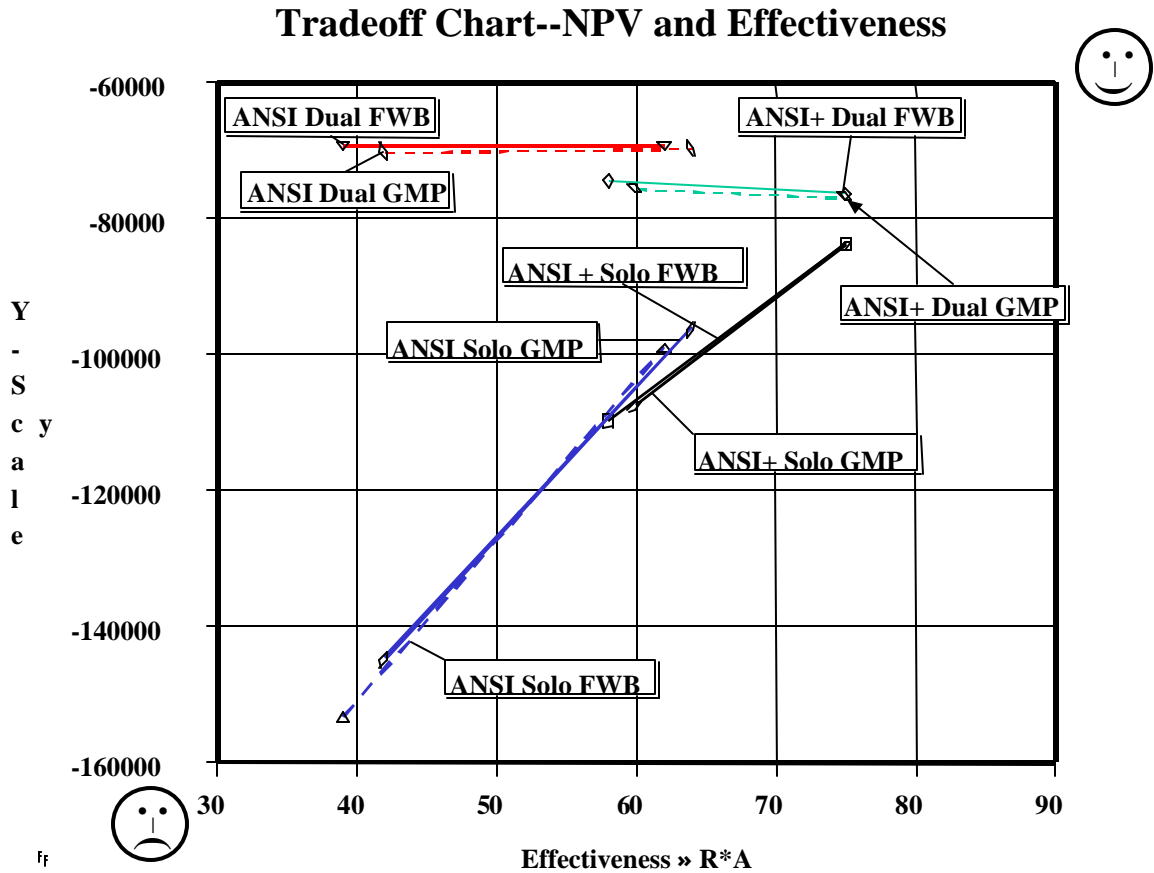


Figure 12: Tradeoff Chart For NPV and Effectiveness

For the pump alternatives shown above, the effectiveness chart is shown in Figure 12 are shown for the better and best practices--notice the happy and unhappy quadrants for the figure.

Figure 12 does not consider the results of capability or maintainability since they are about the same value for each configuration. Also, the effectiveness value is strongly driven by the reliability value. Notice that using good maintenance practices to the ANSI dual pump for best practices of installation and use adds #5 to the effectiveness for a 1% increase in cost. The question each end users must ask, "Is the extra cost worth the extra reliability?"--Figure 12 provides a tool for selling the features. Details for this figure come from Table 12.

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 NPV for investment, failure costs, and power costs is -\$67,728. The NPV for only investment cost is -\$26,058, and the NPV for investment plus power costs is -\$64,995. The effect of power results in a NPV of $-(\$64,995 - \$26,058) = -\$38,937$. The NPV effects of failure costs are the balance or -\$2,733. An approximate Pareto distribution of NPV costs are:

1. Electrical power $38,937/67,728 = 57.4\%$
2. Capital costs $26,058/67,728 = 38.5\%$
3. Failure costs $2,733/67,728 = 4.0\%$

This Pareto distribution of costs for ANSI enhanced dual pumps installed/used with best practices and fix when broken maintenance strategies is informative! One item consists of the vital few--electrical power! The Pareto distribution is shown in NPV terms to see the financial effects with consideration for time value of expenditures. The main issue is power consumption. For this scenario, maintenance costs fall into the trivial portion of NPV considerations.

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/bearing, and energy lost in pump dynamics. High efficiency components can reduce power consumption.

For the pump and motor in the preferred configuration, the highest efficiency components have been selected and thus no other practical devices exist for making a sensitivity analysis except for acquisition costs.

Table 8 shows the inherent reliability of the ANSI enhanced pump has a superior life (2.62 years) compared to the ASNI pump (1.57) years by a factor of $2.62/1.57 = 1.67$ times. Unfortunately the high acquisition cost makes this equipment uneconomical. Perhaps the purchasing department can negotiate a better price for the equipment, which is attached to a very heavy base plate. What is the largest purchase price can we afford to pay for the better equipment and arrive at the lowest NPV? This requires altering NPV's in Table 14 shown below and solving for the lower acquisition cost.

Remember some of the extra costs for alternates 5, 6, 7, and 8 result from heavier equipment, larger foundations, and thus extra installation costs. Thus achieving lower purchase prices to get the better grade of equipment will be a difficult (if not impossible) for the supplier of pumping equipment.

Start the sensitivity analysis for alternatives 5-8 in Table 14 using the NPV results similar to the details shown in Table 11 as each alternative has different acquisition costs and different yearly costs. Then decrease acquisition costs by increments and find the resulting NPV for each alternative in Table 14. Results of the sensitivity studies are shown in Figure 13.

Top Ten Alternatives From Monte Carlo Simulations									
Alternative Rank	Pump Grade	Dual Or Solo	Installation & Use Practice	Maintenance Practice	Capital Cost	NPV	Effectiveness ~ R * A	D % For NPV	D % For NPV
1	ANSI	Dual	Best	Fix When Broken	\$ 30,368	\$(67,728)	62%	-	-
2	ANSI	Dual	Better	Fix When Broken	\$ 27,458	\$(67,901)	39%	-0.3%	-36.9%
3	ANSI	Dual	Best	Good Practices	\$ 30,368	\$(68,225)	64%	-0.7%	4.6%
4	ANSI	Dual	Better	Good Practices	\$ 27,458	\$(68,913)	42%	-1.7%	-31.0%
5	ANSI +	Dual	Better	Fix When Broken	\$ 35,436	\$(72,611)	58%	-7.2%	-6.1%
6	ANSI +	Dual	Better	Good Practices	\$ 35,436	\$(73,864)	60%	-9.1%	-2.3%
7	ANSI +	Dual	Best	Fix When Broken	\$ 39,046	\$(74,253)	75%	-9.6%	21.2%
8	ANSI +	Dual	Best	Good Practices	\$ 39,046	\$(74,994)	75%	-10.7%	22.2%
9	ANSI +	Solo	Best	Fix When Broken	\$ 19,523	\$(82,655)	75%	-22.0%	21.1%
10	ANSI +	Solo	Best	Good Practices	\$ 19,523	\$(82,732)	75%	-22.2%	22.4%

Force To (\$67,728) And Find Required Cost Reduction Trade-up Trade-down

Table 14: Changes Required For Alternatives

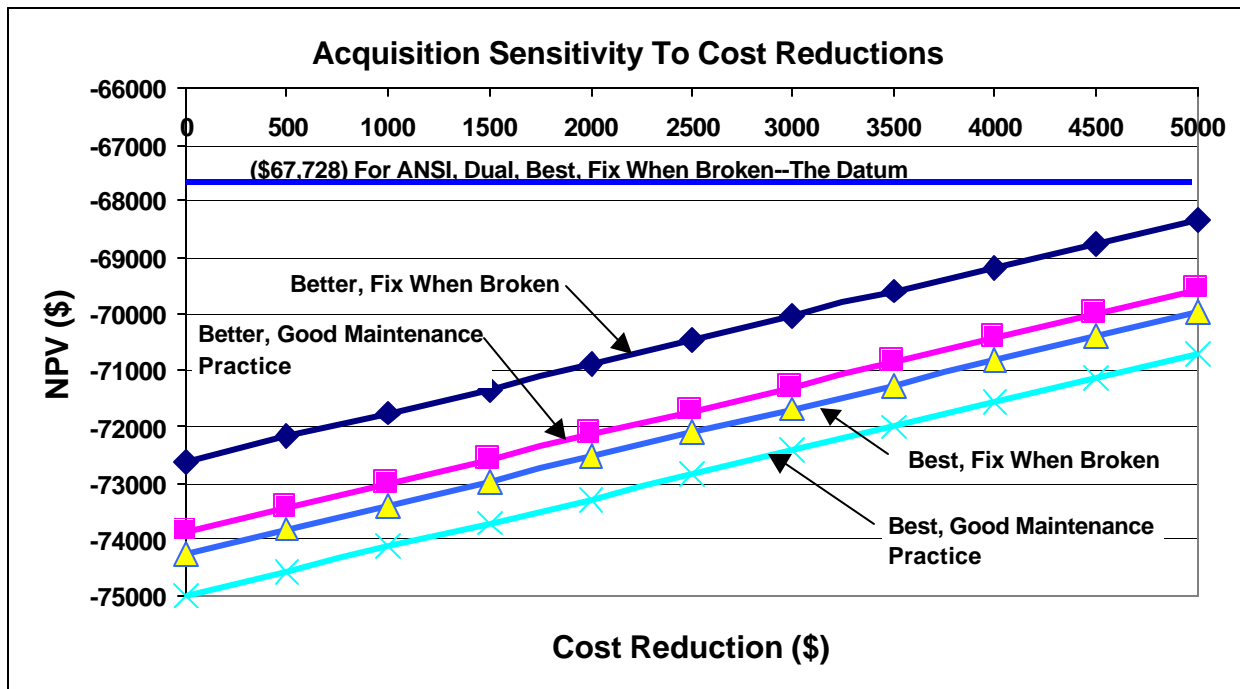


Figure 13: Breakeven Chart For ANSI Enhanced Pumps--Alternatives 5, 6, 7, and 8

Figure 13 show need for major cost reductions (most likely greater than can be achieved in a competitive environment for commodity equipment) if ANSI enhanced equipment is selected. Acquisition cost reductions greater than \$5,000 is required to achieve breakeven shown by the solid horizontal line at (\$67,728) in Figure 10 for alternative 1.

Step 11: Select preferred course of action using LCC.

The selection of a dual pump strategy using ANSI pumps with the best installation and use practices is the most cost effective—Alternative 1. The use of good maintenance practices when components fail will increase the equipment reliability at only modest increases and cost and may be the preferred trade-off alternative—Alternative 3. The ANSI enhanced pump with its extra rigid base plate is not affordable for this condition--the price is too high for value received—our “wants” carry and excessive price greater than our “needs”. Note that Alternate 2 and 4 would be significant set backs in both NPV and effectiveness as costs would be higher and effectiveness would be lower. If you succumb to the cry of “gold plating for the best installation/use” and step down to the lower grade (and less expensive first cost) installation, poorer results will occur.

It is important to remember that each case is specific and do not reach out too far in generalizing about equipment and installations. Situations that are “bad” in one case can be “good” in another when the facts are studied.

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. Performing a Monte Carlo simulation to find costs incurred in each year for wear-out failure modes defers expenditures to later years (compared to constant failure rate models) and this provides advantages for NPV calculations when time effects of money are considered.

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 cost.

A limited subset of the LCC program written in Excel for calculation of the above details is posted for free download from the World Wide Web (Barringer 1998) at <http://www.barringer1.com>.

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