Life Cycle Costs and Weibull Go Together Like PB&J

Abstract: Weibull details are needed to predict end of life for components and systems. When the failures/replacements occur will drive costs during specific project intervals. The cost details from Weibull analysis drive life cycle cost decisions for calculating a key performance indicator represented by a single number for net present value (NPV).

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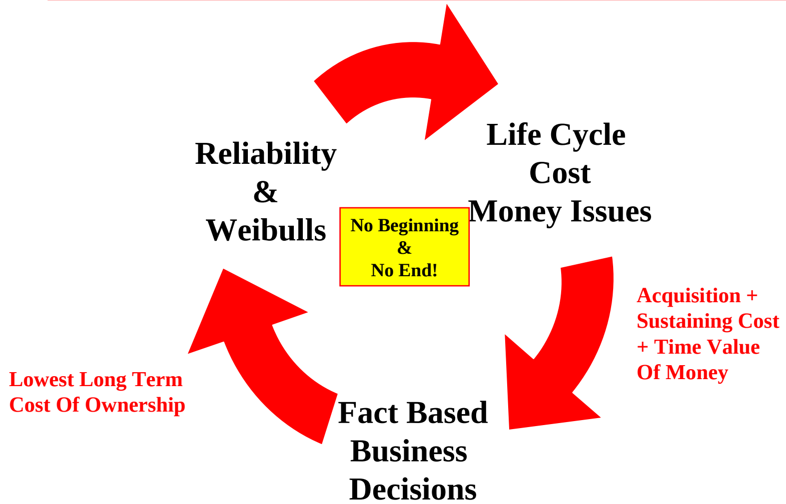
1

Why Do Life Cycle Cost Together and Weibull Distributions Go Together?

Facts About How Things Live and Die → Weibull Distributions → Money Issues



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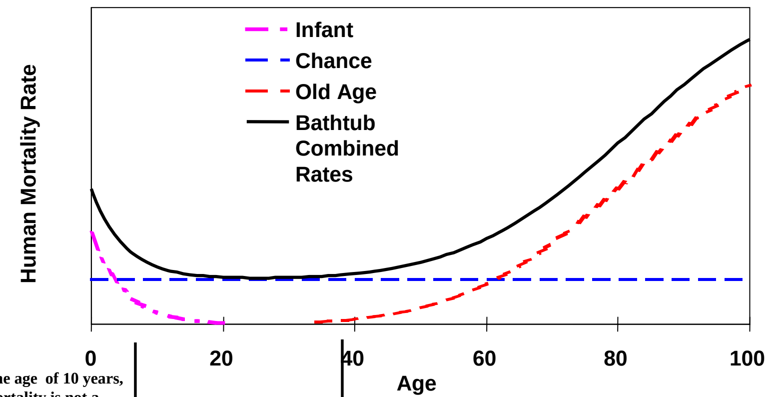
Human Bathtub Curves

From the human experience we get reliability ideas



Beyond the age of 10 years, infant mortality is not a big problem ------------------>

<----------------Beyond age 40, wear-out becomes a problem

The y-axis is more precisely known as the <u>hazard rate</u>. Hazard rate measures the probability a person will die in the next time interval given they survived up to the beginning of the time interval.

Similar curves exist for hardware. They form a survival signature with indications of survival under specific conditions.

Weibull Curves Tell Failure Modes

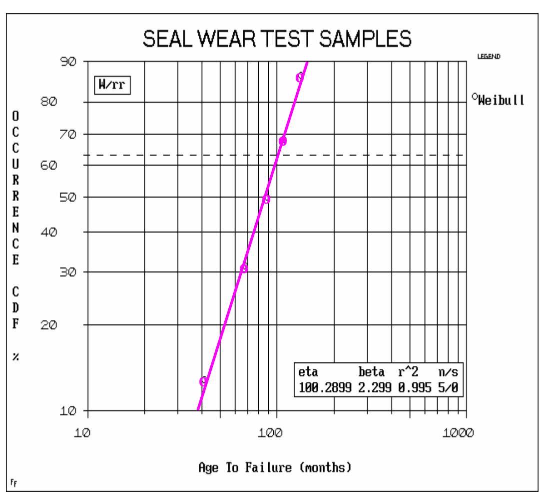
Let Weibull tell you <u>how</u> they died

1. Weibull plots require few data.

2. Weibull plots tell about failure modes.

3. Weibull plots help guide corrective action.

4. Weibull plots are often used with cost data to find least cost actions using risk assessments.



To an engineer, one Weibull graph equals 1000+ words from a statistician!!

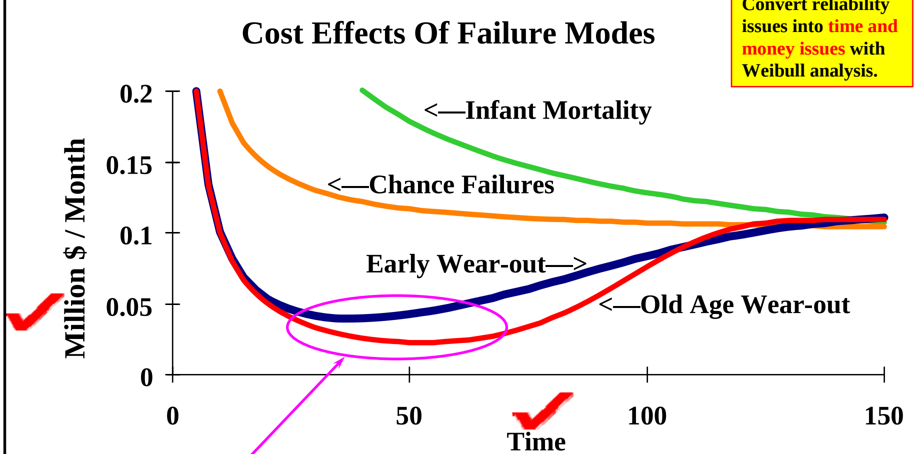
Beta tells the failure mode—**infant mortality, chance failure, or wear out**.

Eta tells the characteristic life.

R^2 tells the goodness of fit.

Maintenance Strategies & Costs

Convert reliability issues into time and money issues with Weibull analysis.



For wear-out problems, minimums can occur only if unplanned cost >> planned costs

5

Solving Reliability Problems With Data

- Improve reliability by solving specific problems —this requires good data and good analysis.
- Good analysis requires good, clean data with measurement of the aging process.
- ! Don't confound aging data with event dependent problems from processes or people ! **Watch out!**
- Identify failure data (including suspensions) by recognizing competing failure modes.
- Use Sherlock Holmes methods and dig through failure data to extracting relevant facts.
- A difficult step of reliability analysis is getting good data—using the data produces better data collection.

6

Data from nuclear power plants

Failures: Roots Of Reliability Problems

Early Plant Life	Frequency %
Design Error	35
Fabrication Error	1
Random Component Failure	18
Operator Error	12
Procedure Error & Unknowns	10
Maintenance Error	12
Unknown	12
	100

Design → People → Component failures

For a modern example see http://www.bpresponse.com

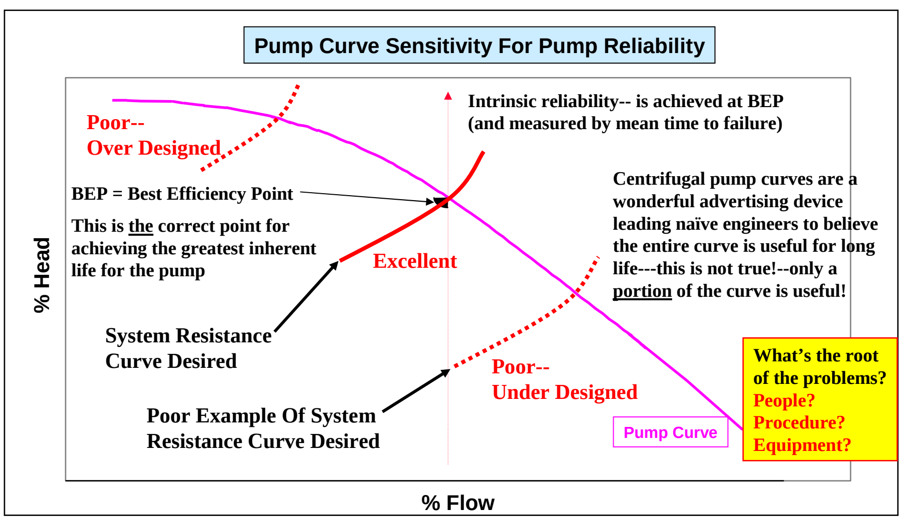
Don't forget MTBSE!

Mature Plants	
People	38
Procedures + Processes	34
Equipment	28
	100

People → Procedures/Processes → Machines

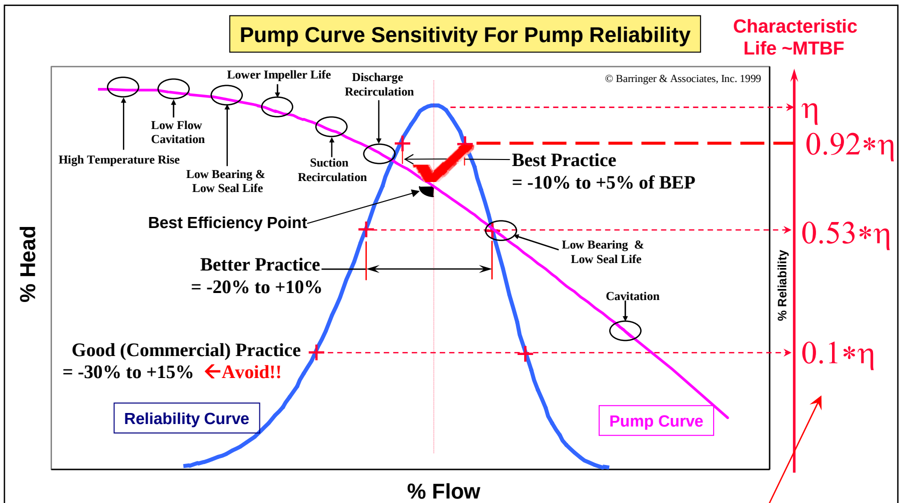
Pump Curve Characteristics

Who is responsible for correct results:
At start-up?
During normal operation
Corrective action?



Pump Curve Practices--A Model

Who sets the standard?
Who communicates standards and reasons for conformance?



This drives life cycle costs

Life Cycle Cost Definitions

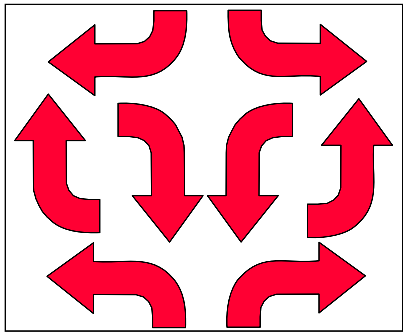
- **Life Cycle Costs--All costs associated with the acquisition and ownership of a system over its full life. The usual figure of merit is net present value.**
- **Net Present Value-- NPV is a financial tool for evaluating economic value added. The** present value of an investment's future net cash flows **(a measure of a company's financial health)** minus the initial investment for a given hurdle discount rate **(the interest rate used in discounting future cash flows) are** summed for the net

Need a life cycle cost Excel work sheet to calculate NPV?
See: http://www.barringer1.com/Anonymous/lcc.xls

Conflicting Issues--What To Do?

Project Engineers:
Minimize capital expenditures

Maintenance Engineers:
Minimize repair hours



Shareholders
Maximize dividends
and/or share price

Production:
Maximize uptime hours

Reliability Engineers:
Maximize equipment reliability
to avoid failures

Buy right? Or
Buy Cheap?

Accounting:
Maximize project net present value

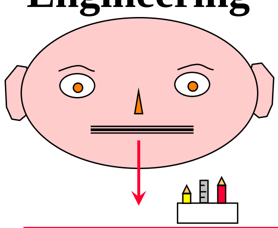
Communication Problems--Boring!!

Boring Beanie Stuff!!!

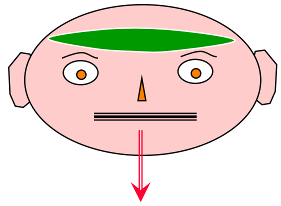
Lack Of Communication
= Anger, Frustration,
And Lack Of Cooperation

Boring Techie Stuff!!!

Engineering



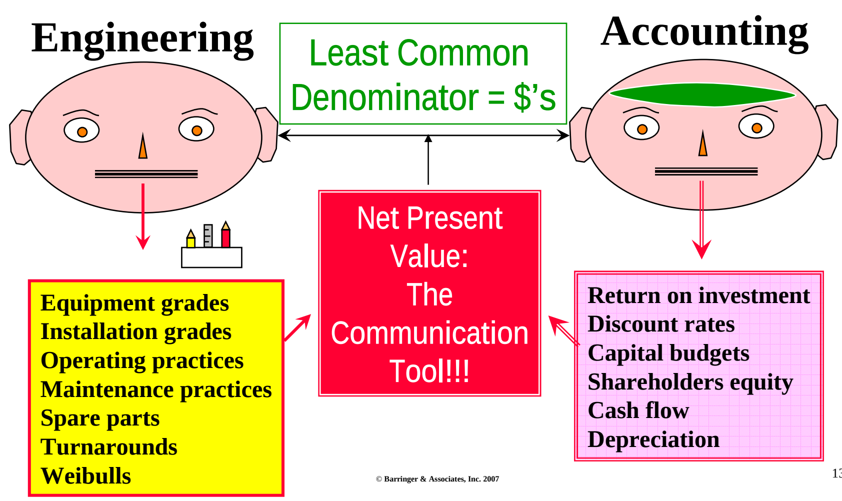
Accounting



Equipment grades
Installation grades
Operating practices
Maintenance practices
Spare parts
Turnarounds

Return on investment
Discount rates
Capital budgets
Shareholders equity
Cash flow
Depreciation

Communication--Money Speaks



13

The Time Value Of Money

Two views of money
1. Present value
2. Future Value

Time Aspects Of Money

Discount Rate = 12%

Years hence	0	1	2	3	4	5	6	7	8	9	10
Present value of US$1.00	$1.00	$0.89	$0.80	$0.71	$0.64	$0.57	$0.51	$0.45	$0.40	$0.36	$0.32
Future value of US$1.00	$1.00	$1.12	$1.25	$1.40	$1.57	$1.76	$1.97	$2.21	$2.48	$2.77	$3.11

Present value of US$1.00 = 1/(1+ i)^n and Future value of US$1.00 = (1+ i)^n

Years hence		11	12	13	14	15	16	17	18	19	20
Present value of US$1.00		$0.29	$0.26	$0.23	$0.20	$0.18	$0.16	$0.15	$0.13	$0.12	$0.10
Future value of US$1.00		$3.48	$3.90	$4.36	$4.89	$5.47	$6.13	$6.87	$7.69	$8.61	$9.65

where i = discount rate and n = number of years into the future

What is the present value (PV) of US$1.00 today over time?
What is the future value (FV) of US$1.00 received over time?

"A bird in the hand is worth two in the bush."
"Money is time and time is money."

14

Engineers Must Quantify All Costs

Can you calculate NPV?

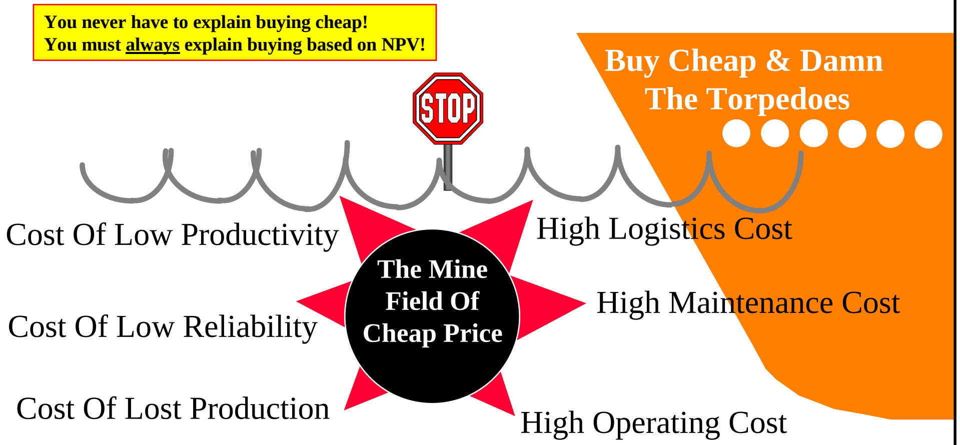
Engineers Must Think Like MBA's
And
Act Like Engineers
To Get
Lowest Long Term Cost Of Ownership
Over The Entire Life Cycle

15

First Cost Is Not The Last Cost

- **Watch out for the lure of cheap first cost!!!!**

You never have to explain buying cheap!
You must <u>always</u> explain buying based on NPV!



16

Why Use LCC

- **Affordability studies**
- **Source selection studies**
- **Design trade-off studies**
- **Repair level analysis studies**
- **Warranty and repair cost studies**
- **Supplier sales strategies**
- **Configure for lowest long term cost of ownership**

Most business are in for the long haul so the lowest cost of ownership (NPV) is best for the business.

LCC Helps Change Perspectives

- Engineering**--show non-redundancy costs**
- Purchasing**--buy right rather than buy cheap**
- Process engineering**--show operating costs**
- Maintenance**--calculate maintenance costs**
- Reliability engineering**--define improvements**
- Management**--operate for lowest long term cost of ownership rather than cheapest first cost**

Everyone has tradeoffs to make.
Don’t operate like ENRON.
Think about the lowest long term cost of ownership for the stockholders!

LCC: A Management Decision Tool

- Provides a costing discipline
- Useful for procurement strategies
- Balances acquisition costs and operating costs
- Useful for trade-off studies based on facts
- Requires engineers to:
  - Think like MBAs for cost considerations
  - Act like engineers by using numbers for decisions
- Requires use of teamwork to generate numbers

Think smart. Act smart. Be responsible. No one has all the answers. Think and act with a conscience!

Engineers And Spreadsheets

- Most financial spreadsheets are generalities because engineers do not give accountants specific equipment details for making accurate financial calculations
- Engineers must add many equipment details to help accountants arrive at the correct economic impact--"I don't have the information" is a void in decision process which drives poor decisions toward bad economic results

If you don't have the information do what they taught you at the university:
1. **Make a hypothesis**
2. **Test the hypothesis**
3. **Use your head! "Common sense is an uncommon virtue." Don't wait!**

What Goes Into Life Cycle Costs?

- Everything goes into LCC and each case is tailored for individual circumstances
- LCC follows a process that fits a simple tree for acquiring data

Management appreciates you following a process more than you as an engineer may appreciate it.

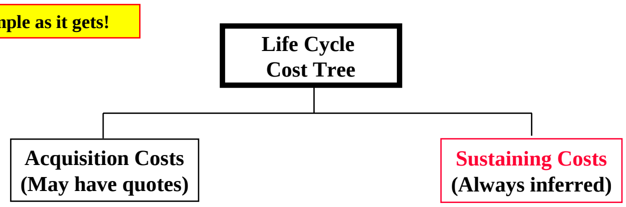
Step	Task
1	Define the problem requiring LCC
2	Alternatives and acquisition/sustaining costs
3	Prepare cost breakdown structure/tree
4	Choose analytical cost model
5	Gather cost estimates and cost models
6	Make cost profiles for each year of study
7	Make break-even charts for alternatives
8	Pareto charts of vital few cost contributors
9	Sensitivity analysis of high costs and reasons
10	Study risks of high cost items and occurrences
11	Select preferred course of action using LCC

Feedback

Top Levels Of The LCC Tree

- **LCC = Acquisition Costs + Sustaining Costs**

This is as simple as it gets!

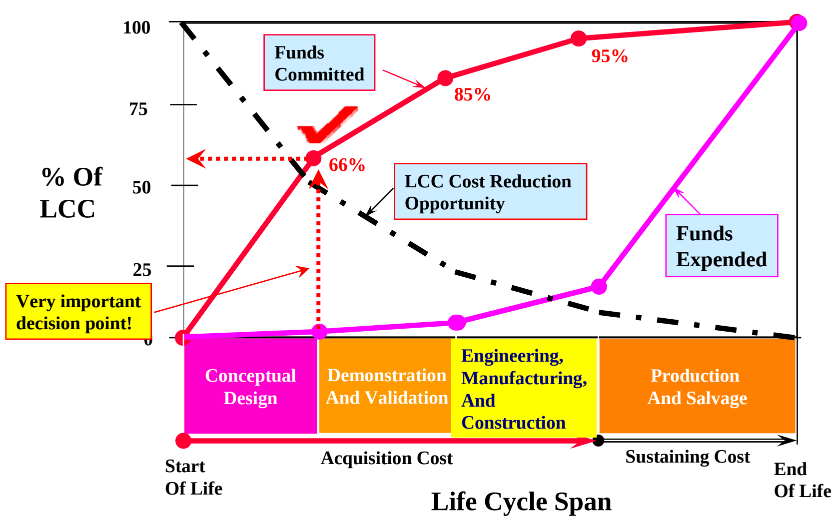


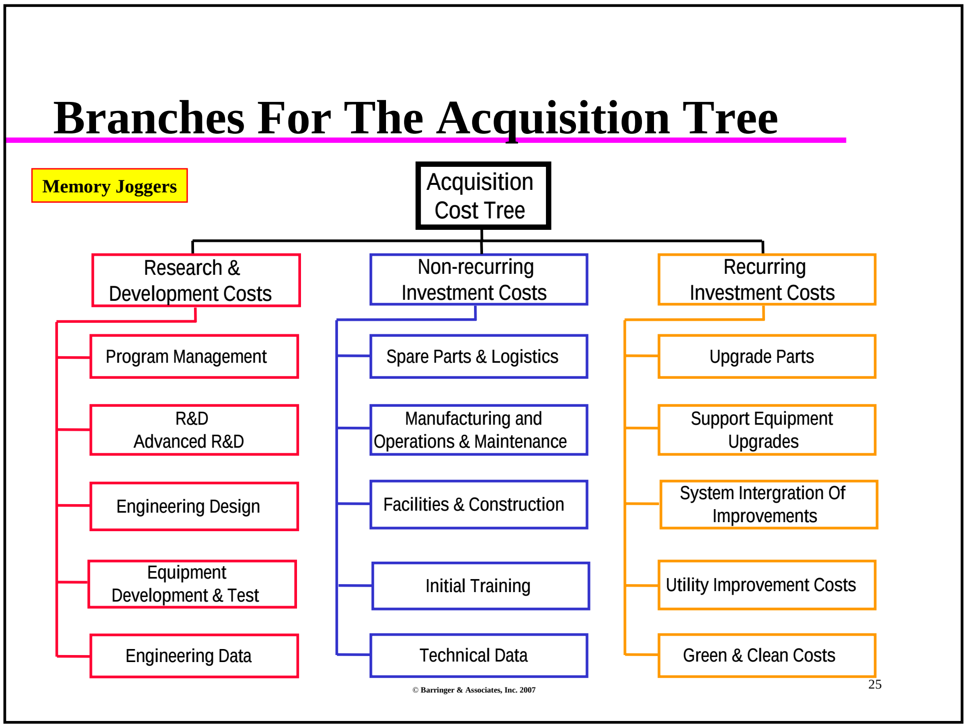
- Acquisition costs and sustaining costs are not mutually exclusive—find both by gathering correct inputs and identifying cost drivers

Hidden Costs Found By LCC

- Often sustaining costs (including hidden costs) are 2-20 times acquisition costs (obvious costs) — **Worry more about sustaining costs!!!**
- About 65%+ of total LCC are fixed by the time equipment is specified (but only a few percent of funds have been expended at this point in time) — **Wham! A key issue!**
- Minimizing LCC pushes up NPV and builds stockholder wealth — **Think long term!**
- Finding the lowest long term LCC requires details for both acquisition costs and sustaining costs requires choices between alternativeS — **Say it in NPV**

Commitments And Expenditures




Branches For The Acquisition Tree
Memory Joggers
Acquisition Cost Tree
Research & Development Costs
Program Management
R&D Advanced R&D
Engineering Design
Equipment Development & Test
Engineering Data
Non-recurring Investment Costs
Spare Parts & Logistics
Manufacturing and Operations & Maintenance
Facilities & Construction
Initial Training
Technical Data
Recurring Investment Costs
Upgrade Parts
Support Equipment Upgrades
System Intergration Of Improvements
Utility Improvement Costs
Green & Clean Costs
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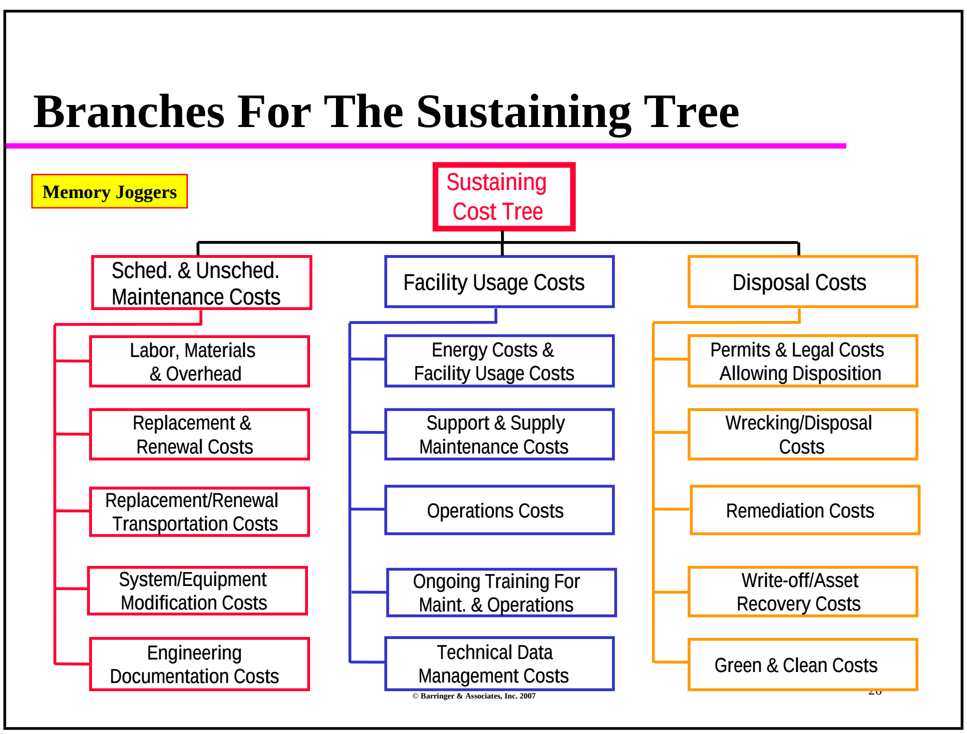
25


Branches For The Sustaining Tree
Memory Joggers
Sustaining Cost Tree
Sched. & Unsched. Maintenance Costs
Labor, Materials & Overhead
Replacement & Renewal Costs
Replacement/Renewal Transportation Costs
System/Equipment Modification Costs
Engineering Documentation Costs
Facility Usage Costs
Energy Costs & Facility Usage Costs
Support & Supply Maintenance Costs
Operations Costs
Ongoing Training For Maint. & Operations
Technical Data Management Costs
Disposal Costs
Permits & Legal Costs Allowing Disposition
Wrecking/Disposal Costs
Remediation Costs
Write-off/Asset Recovery Costs
Green & Clean Costs
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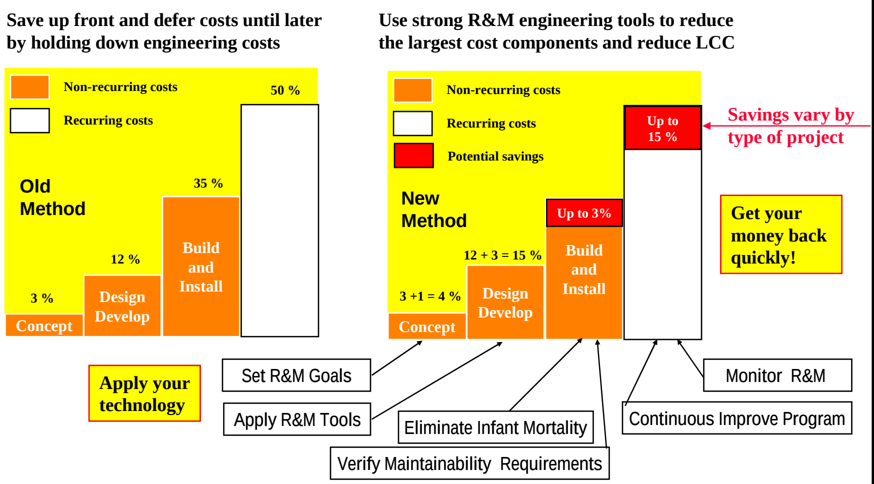
What Costs Goes Where?

- Use common sense
- Each case is special
- Consider the details for BOTH acquisition and sustaining costs to develop the cost schedules
- When in doubt, include the costs
- Don't ignore obvious costs or include trivial costs
- Include the appropriate cost elements and discard the trivial elements--use standard models

Don't make this a career to complete the tasks!

A New View Of R&M Influence On LCC



Source: SAE Reliability and Maintainability Guideline for Manufacturing Machinery and Equipment, 2nd edition, M-110.2

The Big Picture For Each Phase

Short List Of Reliability & Maintainability Activities Over The Life Cycle Phases

The Big PictureTasks	Concept & Proposal Phase	Design & Development Phase	Build & Install Phase	Operation & Support Phase	Conversion Or Decomm. Phase
Set Availability Requirements	X				`
Set Reliability Requirements	X				
Set Maintainability Requirements	X				
Define Functional Failures	X				
Define Environment/Usage	X				
Define Capital Budgets and Make TradeOff Decisions	X	X			
Set Design Margins		X			
Design For Maintainability		X			
Make Reliability Predictions		X			
Do FMEA & Fault Tree Analysis		X			
Do Preliminary Cost Of Unreliability		X			
Conduct Design Reviews		X			
Make Machinery Parts Selections		X			
Do Tolerance/Process Studies		X			
Do Critical Parts Stress Analysis		X			
Do Reliability Qualification Testing			X		
Do Reliability Acceptance Testing			X		
Do Reliability/Maintainability Growth Improvement		X	X	X	
Collect Failure Reports & Analize			X	X	
Provide Data Feedback	X	X	X	X	X

Tailor the matrix to avoid too little or too much emphasis on R&M but meet the needs of the business to make the effort cost effective

Phase 1—Concept/Proposal

Tailor the details to avoid too little or too much emphasis on R&M. Meet needs of the business. Make the effort cost effective! Keep profitability in mind.

R&M Practices For Concept & Proposal Phase

Tasks For Phase 1: Concepts And Proposal	User	Supplier
Preliminary Availabilitly, Reliability, and Maintainability Planning	X	X
Define The Availability, Reliability, and Maintainability Plan	X	X
Implement Lessons Learned	X	X
Specify Availability, Reliability, and Maintainability Requirements	X	
Define How Machinery Will Be Used	X	
Specify Duty Cycles For Equipment	X	
Define Environment For Machinery	X	
Define Continuous Improvement Monitoring	X	X
Define Equipment Life In Throughput Terms	X	
Establish Data Collection Details For R&M	X	X
Develop Application Specific R&M Program Matrix	X	
Develop R&M Program Planning Worksheet Details	X	
Establish Criteria For R&M In Design Reviews	X	X

Design Review Objectives

Concept Review: Focuses on feasibility of the proposed design approach with budget restrictions

Preliminary Design Review: Verifies adaptability of evolving design to meet technical requirements

Final Design Review: Validates the design and analysis are complete and accurate

Build: Addresses issues from equipment build and runoff testing

Installation: Do failure investigation of problems--Do continuous improvement

30

Phase 2—Design & Develop

Reliability & Maintainability Practices For Design & Development Phase

Tasks For Phase 2: Design And Development	User	Supplier
Verify Design Margins (Safety Factors) & Do Stress Analysis		X
Specify How Critical Machinery Components Will Be Selected		X
Do Failure Modes and Effects Analysis:		X
Process FMEA	X	
Machinery FMEA		X
Do Fault Tree Analysis & HAZOPS	X	
Do Design Reviews		X
Do Tolerance/Process Studies		X
Generate Reliability Block Diagrams For Reliability Analysis		X
Do Accelerated Testing To Validate Critical Equipment Details		X
Do Maintainability Design Details To Minimize Downtime/Meet Max Time Limits		X
Define Maintenance Manuals, PM Requirments & CM Details		X
Prepare Spare Parts List & Spare Parts Inventory Plans	X	X
Prepares Details of Built-In Diagnostic Equipment For Maintainabiltiy	X	X
Prepares Details of Captive Hardware For Rapid Maintainability	X	X
Identify Spare Parts To Be Managed Based On Criticality	X	X
Define Maintenance Procedures For Adjustments/Replacements/Repairs	X	X
Define Visual Management Techniques For Workplace Awareness	X	X
Define Modularity Of Physical and Functional Units For Removal/Replacement		X

LCC Requires Facts

- **Based on** “typical” **equipment justifications, equipment** “rarely fails”**—as maintenance cost is not detailed and not preplanned**
- **Real equipment needs constant and expensive maintenance activities--CM, PM, and PdM**
- **Most engineers don’t acknowledge failure data exists and lack training in how to use the data**
- **LCC calculations depend on** equipment facts--not opinions**—and reliability/maintainability details can decrease life cycle cost per SAE**

Get as many facts as you can gather and supplement them with your assumptions. Don’t get bogged down in the trivia—keep some altitude!

Which Equipment To Buy?

A vendor offers three grades of equipment for solving our plant problem. Disregarding depreciation and other accounting details, which grade of equipment should we select for the lowest long term cost of ownership (assume plant life ends after 20 years = 175,200 hours).

	Good	Better	Best
Cost of the new equipment	$50,000 ✔	$75,000	$150,000

Watch out for the lure of cheap first costs!
Which equipment will you buy?--Why
You need details to make the correct decision—
what do you need?

Reliability Models & Costs--Life-Cycle Costs

A vendor offers three grades of equipment for solving our plant problem. Disregarding depreciation and other accounting details, which grade of equipment should we select for the lowest long term cost of ownership (assume plant life ends after 20 years = 175,200 hours). What are the savings?

	Good		Better		Best	
Cost of the new equipment		$50,000		$75,000		$150,000
Failure rate (failures/hour)	0.0005		0.0001		0.00001	
Reliability for a 1 year mission?	_____%		_____%		_______%	
Number of failures in 20 years?	#____		#_____		#______	
20 year failure costs @$5,000/failure?		$_______		$_______		$______
Equipment overhaul required every	5 yr		10		10	
Each overhaul cost is	$10,000		$20,000		$45,000	
20 year number of overhauls & costs?	#____	$_______	#_____	$_______	#_____	$______
Operating/routine maintenance costs	$1.00/hr		$0.90/hr		$0.90/hr	
20 year operating/routine maintenance costs		$_______		$_______		$______
Disposal cost at retirement		$ 5,000		$ 5,000		$ 5,000
Total life time costs (ex depreciation, etc)		$_______		$_______		$______

A quick arithmetic effort with these details can help your NPV decisions?

Long term cost of ownership = Initial cost + maintenance cost (including spares & outside services) + operating costs + disposal costs.

An Arithmetic Model

Watch out for changes in decisions when discount rates are used by accounting.

Reliability Models & Costs--Life Time Costs

A vendor offers three grades of equipment for solving our plant problem. Disregarding depreciation and other accounting details, which grade of equipment should we select for the lowest long term cost of ownership (assume plant life ends after 20 years = 175,200 hours). What are the savings?

	Good		Better		Best	
Cost of the new equipment		$ 50,000		$ 75,000		$ 150,000
Failure rate (failures/hour)	0.0005		0.0001		0.00001	
Reliability for a 1 year mission?	1.25%		41.64%		91.61%	
Number of failures in 20 years?	# 87.6		# 17.52		# 1.752	
20 year failure costs @$5,000/failure?		$ 438,000		$ 87,600		$ 8,760
Equipment overhaul required every	5 yr		10		10	
Each overhaul cost is	$10,000		$20,000		$45,000	
20 year number of overhauls & costs?	# 3	$ 30,000	# 1	$ 20,000	# 1	$ 45,000
Operating/routine maintenance costs	$1.00/hr		$0.90/hr		$0.90/hr	
20 year operating/routine maintenance costs		$ 175,200		$ 157,680		$ 157,680
Disposal cost at retirement		$ 5,000		$ 5,000		$ 5,000
Total long term costs (ex depreciation, etc)		$ 698,200		$ 345,280		$ 366,440

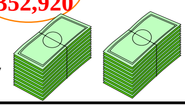
Chance Failures

Wear-out Failures

Save $352,920

Save $21,160

Long term cost of ownership = Initial cost
+ maintenance cost (include spares & outside services)
+ operating costs + disposal costs.



35

NPV For Simple LCC Models--

Arithmetic details converted to NPV.

	Alternative 1	Alternative 2	Alternative 3
Grade	Good	Better	Best
NPV	-$191,861	-$125,465	-$176,556
Reliability	1.25%	41.64%	91.61%

36

Difficulty Of Cost Problems

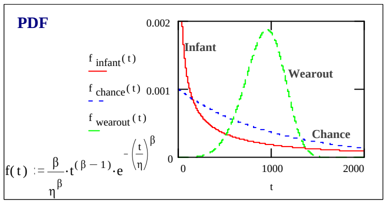
- Problems are easy when the data is "given"
- The hard part is to collect the data
- Some problems are solved at the 65,000' level (few details), the 25,000' level (more details) and most problems are solved at the 2500' level (many details).
- Some costs can be estimated, others must be calculated
- Next we go to more difficult problems--finding the data

Adding Uncertainty Into LCC

- All LCC numbers are uncertain--how much and where is important for final outcomes of cost
- Nothing fails on schedule & nothing runs forever
- Nothing gets repaired in exactly the same time interval
- Failure modes are not always exactly repeated and they are vitally important for RCM strategies
- Uncertainty calculations require use of statistical distributions and Monte Carlo simulations which are best used with Weibull database information

Weibull Statistics: Important LCC Tools

Probability distribution function, f(t)



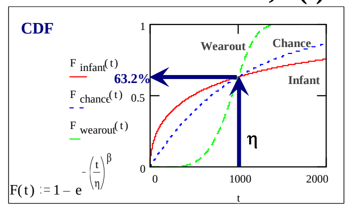
$f(t) := \frac{\beta}{\eta^{\beta}} \cdot t^{(\beta-1)} \cdot e^{-\left(\frac{t}{\eta}\right)^{\beta}}$

η = 1000 <—Characteristic life
β = 5 <—Shape factor
(β has literal interpretations for individual component failures)

MTBF or MTTF = η•Γ(1/β + 1) and when β = 1 then η = Θ

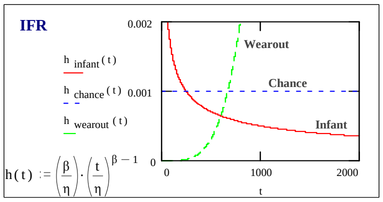
Values used for plots:
β = 0.5 for infant mortality,
1.0 for chance failures
5.0 for wear-out failures
η = 1000 for the characteristic life

Cumulative distribution function, F(t)



$F(t) := 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$

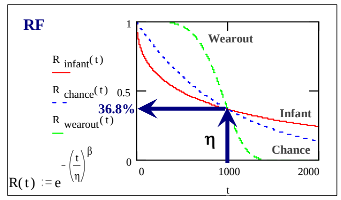
Instantaneous failure rate, h(t)



$h(t) := \left(\frac{\beta}{\eta}\right) \cdot \left(\frac{t}{\eta}\right)^{\beta-1}$

<—Weibull failure rates can represent: infant failure modes, chance failure modes, or wearout failure modes.

Reliability function, R(t) = 1 - F(t)



$R(t) := e^{-\left(\frac{t}{\eta}\right)^{\beta}}$

See Weibull database at: http://www.barringer1.com/wdbase.htm

Weibull Failure Databases

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

- **Use Weibull data and equations to find random times to failure using Monte Carlo methods**

Age-to-failure = t = η*{ln(1/(1-CDF))}^(1/β)
= η*{-ln(1-CDF)}^(1/β) ←Less computer intensive

substitute the Excel function RAND() for CDF

Download this Excel model from http://www.barringer1.com/MC_files/LCC-Simple-Monte-Carlo-Model.zip

Monte Carlo Failures Find Costs

Individual Failure Iteration--->

Cumulative Iterations--->

Annualized Failures--->

Costs Of Failures--->

Solo ANSI Pump Fix When Broken Life Cycle Cost Simulation In An Excel Spreadsheet

Cost Element	η	β	1st Age To Failure	1	2	3	4	5	6	7	8	9	10
a) Individual Iteration				Project Year Of Replacement And Number Of Replacements Required									
Electricity													
Seal	3	1.4	1.28	0	1	2	0	0	0	0	1	0	0
Shaft	18	1.2	9.26	0	0	0	0	0	0	0	0	0	1
Impeller	12	2.5	13.28	0	0	0	0	0	0	0	0	0	0
Housing	18	1.3	49.44	0	0	0	0	0	0	0	0	0	0
Pump Bearings	4	1.3	9.03	0	0	0	0	0	0	0	0	0	1
Motors	12	1.2	17.31	0	0	0	0	0	0	0	0	0	0
Coupling	8	2.0	5.53	0	0	0	0	0	1	0	0	0	0
Hours Down Time For This Iteration =				0.00	8.00	16.00	0.00	0.00	8.00	0.00	8.00	0.00	18.00
Number Of Failures For This Iteration=				0	1	2	0	0	1	0	1	0	2
Cumulative Number Of Suspensions=				0	0	0	0	0	0	0	0	0	0
b) Cum. Iterations-->	**10000**			Project Year Of Replacement And Cumulative Number Of Replacements Required									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity													
Seal	3	1.4		1997	3051	3469	3573	3617	3647	3581	3664	3639	3636
Shaft	18	1.2		296	383	432	516	463	500	519	508	538	578
Impeller	12	2.5		19	82	207	301	460	575	700	780	891	995
Housing	18	1.3		220	323	396	458	417	462	485	528	543	512
Pump Bearings	4	1.3		1563	2284	2529	2632	2659	2591	2730	2711	2688	2673
Motors	12	1.2		500	630	747	704	759	798	793	790	809	791
Coupling	8	2.0		153	451	779	955	1159	1266	1351	1416	1421	1451
Cumulative Hours Down Time =				39896	60336	71712	76884	79700	82468	85228	87360	88566	89308
Cumulative Number of Failures=				4748	7204	8559	9138	9534	9837	10160	10397	10529	10635
c) Annual Failures Expected				Project Year And Average Number Of Failures Required Each Year									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity													
Seal	3	1.4		0.200	0.305	0.347	0.357	0.362	0.365	0.358	0.366	0.364	0.364
Shaft	18	1.2		0.030	0.038	0.043	0.052	0.046	0.050	0.052	0.051	0.054	0.058
Impeller	12	2.5		0.002	0.008	0.021	0.030	0.046	0.058	0.070	0.078	0.089	0.100
Housing	18	1.3		0.022	0.032	0.040	0.046	0.042	0.046	0.049	0.053	0.054	0.051
Pump Bearings	4	1.3		0.156	0.228	0.253	0.263	0.266	0.259	0.273	0.271	0.269	0.267
Motors	12	1.2		0.050	0.063	0.075	0.070	0.076	0.080	0.079	0.079	0.081	0.079
Coupling	8	2.0		0.015	0.045	0.078	0.096	0.116	0.127	0.135	0.142	0.142	0.145
Average Down Time Hours For All Iterations=				3.99	6.03	7.17	7.69	7.97	8.25	8.52	8.74	8.86	8.93
Average Number Of Failures/year For All Iterations=				0.47	0.72	0.86	0.91	0.95	0.98	1.02	1.04	1.05	1.06
d) Annual Cost Expected For Each Time Interval				**Project Year And Annual Costs Expected From Simulation**									
Cost Element	η	β		1	2	3	4	5	6	7	8	9	10
Electricity	--	--		16500	16500	16500	16500	16500	16500	16500	16500	16500	16500
Seal	3	1.4		6865	10488	11925	12282	12433	12537	12310	12595	12509	12499
Shaft	18	1.2		1296	1678	1892	2260	2028	2190	2273	2225	2356	2532
Impeller	12	2.5		69	296	747	1087	1661	2076	2527	2816	3217	3592
Housing	18	1.3		1351	1983	2431	2812	2560	2837	2978	3242	3334	3144
Pump Bearings	4	1.3		5185	7577	8390	8732	8821	8596	9057	8994	8917	8868
Motors	12	1.2		1815	2287	2712	2556	2755	2897	2879	2868	2937	2871
Coupling	8	2.0		513	557	606	633	663	680	692	702	703	707
Maintenance PM visits				$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600	$ 600
Operations PM visits				$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364	$ 364
Vibration Dept				$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520	$ 520
Training costs				$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128	$ 128
Total				**$35,205**	**$42,977**	**$46,815**	**$48,473**	**$49,034**	**$49,922**	**$50,827**	**$51,553**	**$52,084**	**$52,324**
Approximate suspensions per failure=				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Approximate system failure rate (failures/yr)=				0.47	0.72	0.86	0.91	0.95	0.98	1.02	1.04	1.05	1.06
Approximate system MTBF(years/failure) =				2.11	1.39	1.17	1.09	1.05	1.02	0.98	0.96	0.95	0.94
Theoretical 1 yr Reliability =				60.5%									
# of iterations->	**10000**	1 yr reliability, R=		62.2%	48.7%	42.5%	40.1%	38.5%	37.4%	36.2%	35.4%	34.9%	34.5%
Fix When Broken Strategy		1 yr Availability, A=		99.95%	99.93%	99.92%	99.91%	99.91%	99.91%	99.90%	99.90%	99.90%	99.90%

←Metrics

NPV

41

LCC Summary

Want more to read? See: http://www.barringer1.com/lcctrng.htm

- Life cycle costs include cradle to grave costs
- Including Weibull failures into LCC decisions permits engineering quantities of resources
- LCC provides a visualization technique for trade-off studies and uses NPV for sound decisions
- Monte Carlo models add realism to numbers
- Good engineering produces LCC alternatives to search for the lowest long term cost of ownership
- In the end, the effort is all about the money and Weibull analysis is a key tool to get to the money!
- Weibull distributions and LCC go together like peanut and jelly sandwiches for great results!

42