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Life Cost-Based FMEA Using Empirical Data

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ABSTRACT

Failure Mode and Effect Analysis (FMEA) is a design tool that helps designers identify risks. The traditional FMEA involves ambiguity with the definition of risk priority number: the product of occurrence, detection difficulty, and severity subjectively measured in a 1 to 10 range. Life-cost Based FMEA alleviates this ambiguity by using the estimated cost of failures. Yet, the methods still relies on judgment of experts in determining variables such as frequency, detection time, fixing time, delay time, and parts cost. To resolve this subjectivity, this paper proposes a systematic use of empirical data for applying life-cost-based FMEA. A case study of a large scale particle accelerator shows the advantages of the proposed approach in predicting life cycle failure cost, measuring risk and planning preventive, scheduled maintenance and ultimately improving up-time.

Keywords: FMEA, Life Cost-Based FMEA, Empirical Data, Failure Cost

1. INTRODUCTION

The main objective of Life Cycle Cost (LCC) analysis is to quantify the total cost of ownership of a product throughout its full life cycle, which includes research and development, manufacturing, operation and maintenance, and disposal. The predicted LCC is useful for decision making in designing, optimizing design, and scheduling maintenance. It is believed that a typical range of ownership cost is 60 to 80 percent of the total LCC. For instance, a typical ownership of a fighter aircraft is 70% of the total LCC (SAE).

The most important task for design engineers is to perform tradeoff analysis between cost and performance. Therefore, it is important to develop a method that gives designers quick and accurate feedback on the life cycle cost of their design decisions in order to determine the optimal design. Several different approaches have been developed to help designers with this matter. Heuristic models, which are developed through the use of computer simulation, can only be used for the specific situation for which they were intended. (Gupta, 1983) Artificial neural networks have been utilized to explore approximate estimation of a product life cycle cost during conceptual design (Seo, 2002). The concept of service mode analysis (SMA) as an evaluation method for design for serviceability has been developed to focus on service needs in estimating life cycle ownership cost. (Gershenson, 1992)

Although these methods are useful, they neglect to capture failures that occur during the early part of product development. Failure Mode and Effect Analysis (FMEA) is most effective in capturing all types of failure modes throughout the life cycle of a product. However, traditional FMEA has some shortcomings: 1) The detection index does not accurately measure contribution to risk, and 2) The risk priority number (RPN) is a product of 3 ordinal numbers. (Kmenta, 2000) These shortcomings of traditional FMEA were resolved through the introduction of a Life Cost-Based FMEA (Rhee, 2002). Life Cost-Based FMEA measures failure/risk in terms of cost. Failures may occur at any stage of the product development life cycle: design, manufacturing, installation, and operation. Failure cost becomes greater as the origin and detection stages of a failure become further apart in time. Failure cost has three major components: labor cost, material cost, and opportunity cost.

Labor cost and opportunity cost are measured in terms of time and are broken up into four different stages: detection time, fixing time, delay time, and recovery time. Component replacement due to failure is considered as material cost.

Experts in the field usually predict occurrence rates for individual types of failures. However, predictions have much uncertainty, leading to wide ranges of predicted costs. It is desirable to minimize uncertainty in predicting failure cost. This paper will discuss the utilization of empirical data to determine occurrence rates and detection, fixing, and delay times for Life Cost-Based FMEA.

The case study for this paper was done in conjunction with and supported by research and development being performed at the Stanford Linear Accelerator Center (SLAC) for a particle accelerator called the Next Linear Collider (NLC). All of the quantitative estimates in this work should be considered as illustrative only, and do not reflect what the actual costs might be at some time in the future.

2. APPLYING EMPIRICAL DATA ON LIFE COST BASED FMEA

2.1. Availability Modeling

In electrical power plant and chemical process industries, LCC analysis is more closely linked to system availability analysis than other industries, because production regularity is one of the biggest concerns for plant owners. LCC analysis in plant industries tends to focus on prediction of the unavailability of the total system due to component failures, maintenance and emergency shutdowns.

The availability of a repairable component is approximated as expressed in Equation (1), if after each repair "as good as new" is assumed. (Birolini, 1997)

- **Availability:** Average probability that an item will perform its required function under given conditions at time.

$$Availability \quad (A) = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF} \qquad (1)$$

- **MTBF (Mean Time Between Failures):** MTBF is a basic measure of reliability for repairable items. It can be described as the number of hours that pass before a component, assembly, or system fails. It is a commonly used variable in reliability and maintainability analyses.

- **MTTR (Mean Time to Repair):** MTTR is the average time required to perform corrective maintenance on all of the removable items in a product or system. This kind of maintainability prediction analyzes how long repairs and maintenance tasks will take in the event of a system failure.

- **MTTF (Mean Time To Failure):** MTTF is a basic measure of reliability for non-repairable systems. It is the mean time expected until the first failure of a piece of equipment. MTTF is a statistical value and is meant to be the mean over a long period of time and large number of units.

Failure rate, μ, can be expressed in the following way:

$$\mu = \frac{1}{MTBF} \qquad (2)$$

The method mentioned above can be applied to predicting the availability for systems or subsystems. Availability of a subsystem that has many components of the same type in series can be modeled using the following equation:

$$Availability_{Subsystem} = (Availability_{1Component})^{\#ofComponents} \qquad (3)$$

2.2 Applying Data to Life Cost-Based FMEA

We can predict failure frequency for a given time once the availability has been calculated. Downtime for the system is calculated using the following equation:

$$Downtime = (1 - Availability) \times OperationTime \qquad (4)$$

Knowing MTTR from empirical date, the average failure frequency for a given time can be predicted using the following equation:

$$Frequency = \frac{Downtime}{MTTR} \qquad (5)$$

The predicted frequency is ready to be utilized for the Life Cost-Based FMEA sheet. Failure modes for water-cooled particle accelerator electromagnets were identified and listed on the far left column in Table 1. If the origin of the failure is during operations, it is most likely that the failure will reoccur during the life cycle of the product. However, if the origin of the failure is in design, manufacturing, or installation it is most likely to be a one-time occurrence. Thus, "30" is denoted under the "Reoccurrence" column for failures that occur during the operation stage of the linear collider. "30" represents the number of years the linear collider is expected to operate for this analysis. For the case of failures that occur during design, manufacturing, and installation periods, "1" is denoted under the "Reoccurrence" column. Failure frequency is predicted using empirical data is an input in Life Cost-Based FMEA. Detection time, fixing time, and delay time are also determined using empirical data.

Table 1. Life Cost-Based FMEA Table

Partial List of Failures	Scenario	End Result	Origin	Detection Phase	Reoccurrence	Frequency	Detection Time	Fixing Time	Delay Time	Down Time	Quantity	Parts Cost ($)	Labor Cost ($)	Material Cost ($)
Thermal switch trip due to overheating	Too many loads on water circuit	Magnet turned off	Oper	Oper	30	0.01	0.5	4		4.5	1	50	180	15
	Conducter Sclerosis (hole gets too small)	Magnet turned off	Oper	Oper	30	0.5	1	8		9	1	1250	18000	18750
	Water passage is blocked due to foreign object	Magnet turned off	Oper	Oper	30	2	1	4		5	1	50	38400	3000
	Damaged (crimped) coil	Magnet turned off	Inst	TR	1	4	0.5	2		0	1	1250	1280	5000
	Water sprayed onto the coil		Oper	Oper	30	3	2	8		10	1	50	115200	4500
										0			0	
Short at jumpers	Poor jumper design	Magnet turned off	Des	DR	1	0.2	1	8		0	40		8976	
	Bad Installation (Bolts not tight)	Magnet turned off	inst	TR	1	4	0.5	2.5		0	1	10	1560	40
										0			0	
Loose jumpers	Loose terminal connection design	Excessive heat lead to melting temp	Mfg	Test	1	0.011	1	8		0	40		493.68	
	Loose Jumpers	Excessive heat lead to melting temp	Mfg	Test	1	4	0.5	2.5		0	1	100	1560	400
										0			0	
Magnet overheats	Poor terminal connection design	Excessive heat lead to melting temp	Des	Test	1	0.011	1	8		0	40	100	493.68	44

One can derive the labor cost for each failure mode from the life cost-based FMEA table using the following equation:

$$\text{Labor Cost} = \text{Frequency} \times \{[\text{Detection Time} \times \text{Labor rate} \times \text{\# of operators}] + [\text{Fixing Time} \times \text{Labor rate} \times \text{\# of operators}] + [\text{Delay Time} \times \text{Labor rate} \times \text{\# of operators}]\} \times \text{Reoccurrence} \quad (6)$$

Component replacements due to failure in particular components are considered as material cost. Material cost is obtained using the following equation:

$$\text{Material Cost} = \text{Frequency} \times \text{Reoccurrence} \times \text{Quantity} \times \text{Cost of Part} \quad (7)$$

Opportunity cost is the cost incurred when a failure inhibits the main function of the system and prevents any creation of value. Opportunity cost is calculated using the following equation:

$$\text{Opportunity Cost} = \text{Down Time} \times \text{Hourly Opportunity Cost} \quad (8)$$

where,

$$\text{Down Time} = \{\text{Detection Time} + \text{Fixing Time} + \text{Delay Time}\} \quad (9)$$

Although empirical data for average frequency, detection time, fixing time and delay time can be obtained it is still dangerous to use point estimation. Any decisions based on average conditions could be incorrect since one does not know if the condition has reached the upper or lower thresholds. A sensitivity analysis on the estimates will provide better confidence in the result. A Monte Carlo simulation is applied to the Life Cost-Based FMEA to perform a sensitivity analysis on variables related to failure cost: occurrence, detection time, fixing time, delay time and material cost. A triangular distribution using minimum, mode, and maximum value was used. The results are discussed in section 4 of this paper.

3. ACTUAL APPLICATIONS

The Stanford Linear Accelerator Center (SLAC) is a national research laboratory that is charged with investigating the most basic elements of matter. Engineers at SLAC and other labs are currently designing the Next Linear Collider (NLC) that will be 20 miles long, 10 times longer than the current linear accelerator at SLAC. The proposed Next Linear Collider (NLC) has a proposed 85% overall availability goal, the availability specifications for all its 7200 magnets and their 6167 power supplies are 97.5% each. SLAC intends to operate the NLC 24 hours per day, 7 days a week for 9 months a year. Thus, all of the electromagnets and their power supplies must be highly reliable or quickly repairable to minimize interruption of the particle physics research program.

SLAC keeps a history of all failures for the past 15 years on an online database called the Computer Aided Trouble Entry and Reporting (CATER) system. (Sass, 1993) Thus, empirical data from SLAC's accelerator failure database and design experience are used to calculate Mean Time Between Failures (MTBF) for failures modes identified using FMEA. Occurrence or probability for certain failure modes can be determined through MTBF. The NLC requires 7167 magnets to control its particle beams. Two different technologies could be used for the magnets: electromagnet or permanent magnets.

An electromagnet's strength is varied by changing the electric current in the coils. Thus, a power supply is required as part of the system. SLAC has been using more than 3000 electromagnets over the past 30 years and their failure data are readily available. Another competing technology uses permanent magnets without any current. Permanent magnets are simpler in design and the initial manufacturing cost maybe smaller. However, the technology risk has not been ascertained for adjustable permanent magnets.

This paper describes the utilization of empirical data to estimate failure/risk cost for electromagnets. 129 different types of electromagnets for the NLC are categorized into 2 fundamental designs: water-cooled and solid wire electro magnets.

3.1. Electromagnet

History of magnet failures from 1997 to 2001 was collected using the SLAC CATER system. Table 2 shows a total of 76 incidents where a beam line had to be shutdown due to electromagnet failures. 90% of the failure incidents and 96% of the total downtime were associated with water-cooled electromagnets.

Table 2. Downtime of Accelerator Due to Magnet Failure

	Events	Total Downtime	Min	Max	Avg
Solid Wire	6	25.8	1.8	11	4.3
Water Cooled	70	699.2	0.1	32	10.0
Total	76	725			9.5

Units: hour

Table 3 shows the five most common failure modes with electromagnets and its frequency and downtime. Insulation failures are related to magnets becoming shorted. The insulation material around the coil becomes degraded due to radiation or thermal effects. Water leaks from the cooling system is a major problem with electromagnets. Water leaks are mainly due to failures in flexible hoses and copper corrosion. Human errors range from not following procedures or forgetting tasks. Connector failures are mainly mechanical failures due to mechanical and thermal cycling.

Table 3. Failure Frequency and Downtime of Electromagnets

Failure Mode	Events	Min(hr)	Max(hr)	Avg(hr)
Insulation	29	0.2	27.2	8.82
Water Leak	22	1	32	9.7
Water Blockage	5	0.5	7.5	3.92
Human Error	5	0.7	6	2.5
Connector	3	1	3.2	1.733
Other	12	0.9	10.2	5.8

If the NLC were to be built using all electromagnets, the NLC would have 2202 solid wire and 4965 water-cooled electromagnets. All 7167 electromagnets are needed for the accelerator to run. Thus, if one magnet fails the whole accelerator will come to a stop. We can estimate the availability of the magnet system (A_{Sys}) using the following equation:

$$A_{Sys} = (A_{1C})^{n} \qquad (10)$$

where, A_{1C} is the availability of one component and n is the total number of components in the system.

Table 4 shows the different types of beamlines and their durations during the period from 1997 to 2002. The second column indicates the type of line running during the period. The third column shows the number of water-cooled electromagnets for that particular line. The fifth column is the product of run hour and the number of magnets: magnet hours. The sixth column indicates the number of failures identified during that particular period. The MTBF in the seventh column is a result of magnet hours divided by the number of failures. The eighth column indicates the total repair time for those failures in that period and the ninth column is MTTR. Based on these numbers the availability of any one magnet in a

Table 4. Run Time of Water Cooled Electromagnet

By Run Time (Water Cooled Magnets)									
Date	**Line**	**Run Hour**	**Magnets**	**Magnet Hours**	**# Failures**	**MTBF**	**TR**	**MTTR**	**Availability 1 Mag**
2/4/97 - 4/30/97	Linac/BSY	1547	520	804440	1	804440.0	0.2	0.20	0.999999751
5/1/97 - 6/8/98	SLC	8828	2104	18574112	32	580441.0	469.5	14.67	0.999974724
7/10/98 - 7/31/98	HER&LER	575	2433	1398975	2	699487.5	9	4.50	0.999993567
10/30/98 - 12/15/98	HER&LER	1040	2433	2530320	6	421720.0	40.1	6.68	0.999984152
1/15/99 - 2/22/99	HER&LER	844	2433	2053452	4	513363.0	15.6	3.90	0.999992403
2/24/99 - 5/1/99	Linac	1461	520	759720	2	379860.0	26.1	13.05	0.999965646
5/1/99 - 11/29/99	HER&LER	4797	2433	11671101	7	1667300.1	65.65	9.38	0.999994375
1/12/00 - 10/31/00	HER&LER	6624	2433	16116192	7	2302313.1	34.6	4.94	0.999997853
1/10/01 - 12/31/01	HER&LER	7411	2433	18030963	7	2575851.9	37.9	5.41	0.999997898
Sum				75,475,138	70		701.70		
Average						1,078,216		10.02	0.9999907029
		Magnets			System				
Actual	**PEP II**	2433		Availability	0.984009931				0.999993375
Actual	**SLC**	2104		Availability	0.948207061				0.999974724
Predicted	**NLC**	4965		Availability	**0.95488886**				
	Forecast for NLC								
	Operation Hr/yr	6480							
	Expected Downtime	292.3	hr/year						
	Occurrence/yr	29.2							

beamline can be calculated. The average availability of one water-cooled magnet at SLAC is found to be 0.9999907.

The availability of the NLC's electromagnet subsystem can be estimated using Equation (3). Assuming the reliability of each individual magnet is 0.9999907 the availability for 4965 water-cooled electromagnets would be 0.9548. However, this is lower than the target value of 97.5% for the magnet subsystem. Therefore the magnet designers know they must improve the reliability of the magnets they design for NLC over the SLAC magnets. Given 6489 hours of operation time per year, the expected downtime of the NLC due to electromagnet failure is 292 hours/year. Since the average MTTR is 10 hours, we can estimate the number of failures for a given year to be 29 occurrences.

Availability of solid wire magnets can be calculated in the same manner. The expected number of failures for solid wire magnets in the NLC is twice a year. The overall availability of the NLC magnet system is obtained using the following equation:

$$\begin{aligned} A_{MSys} &= A_{SM} \times A_{WM} \\ &= 0.9987 \times 0.9549 = 0.9536 \end{aligned} \tag{11}$$

A_{SM} = *Availability of solid wire magnet*
A_{WM} = *Availability of water-cooled magnet*

Thus, this would fall short of the 97.5% availability goal if the design of the new magnets does not eliminate the root cause of the observed failures. A summary of the availability is shown in Table 5.

Table 5. Predicted Availability of Electromagnets for NLC

Type	Solid Wire	Water-cooled
# of Magnets	2202	4965
Availability	0.9987	0.9548
Expected Downtime	8.3 hrs/yr	292 hrs/yr
Occurrence	1.9 / yr	29.2 /yr

This example predicts the overall failure for the NLC, but one can predict failures for particular types of failure (insulation, water leak, water blockage, mechanical, or human error) using the same methodology.

3.2. Power Supply

The power supplies that provide the electric current to the electromagnets can be categorized into 2 main categories: small (< 12Amps, 50Volts) and large (> 12Amps, 50Volts). A summary of the SLAC power supply failures from the CATER system between 1997 and 2001 is shown in Table 6. The total number of failures is 2.5 times greater than the number of electromagnet failures but the total downtime is less than half of the electromagnet failures. This is because the average downtime for power supply is only 1.65 hours as opposed to 9.5 hours for the electromagnet. Only failures that required the accelerator to shutdown were considered.

Table 6. Downtime of Accelerator Due to Power Supply Failure

Type of PS	Events	Total Down Time	Max	Min	Avg Down Time
Large	92	178	11	0.1	1.93
Small	70	88.7	11.5	0.2	1.27
Total	162	266.7	32	0.1	1.65

Units: Hour

Availability, MTBF, and occurrence for the power supplies can be estimated following the same steps as in the electromagnets. The results are shown in Table 7.

Table 7. Predicted Availability of Power Supplies for NLC

Size	Small	Large
# of Power Supplies	2785	3382
Availability	0.988	0.938
Expected Downtime	77 hrs/yr	400 hrs/yr
MTBF	105 hrs	32 hrs

The overall availability of the power supply system (A_{PSSys}) is the product of the two types of power supplies: small and large.

$$A_{PSSys} = A_{SPS} \times A_{LPS} = 0.988 \times 0.938 = 0.927$$

A_{SPS} = *Availability of Small Power Supply*
A_{LPS}= *Availability of Large Power Supply*

This is far short of the 97.5% availability requirement. Thus, the reliability of the power supply has to be increased. One way of achieving this is to design redundancy in the system. Since the small power supply has a high availability rate, we will consider having redundancy only in larger power supplies to minimize cost. With redundancy in large power supplies (A_{LPS}), the power supply availability becomes 0.986.

$$\textit{Improved } A_{PSSys} = 0.988 \times 0.9975 = 0.986$$

The expected downtime due to power supply failure is 6480 hours x (1-0.9855) = 93.9 hours/yr. Using the average fixing time for the power supply, 1.5 hours, the average number of failure during the year is 93.9 / 1.5 = 62 events/year.

3.3. Electromagnet System

The electromagnet system has power supplies that control the electric field for each magnet as shown in Figure 1 schematically. The larger water-cooled magnets will have redundant power supplies since the availability of a single power supply is too low. The accelerator will shutdown if any one of the 7167 magnets or 6167 sets of power supply fail. Thus, the availability of the system is the product of the magnet and power supply availabilities.

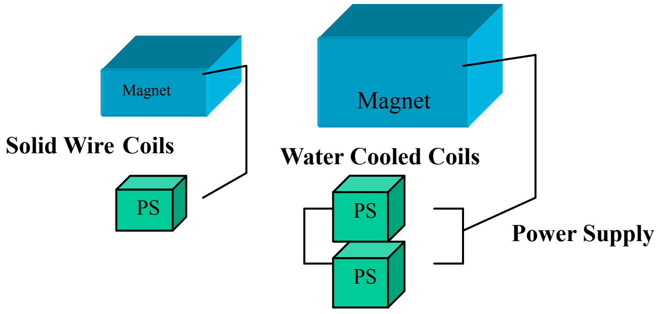

Figure 1. Electromagnet System

$$A_{Sys} = A_{MSys} \times A_{PSSys} = 0.9536 \times 0.986 = 0.94$$

$$\begin{aligned} \text{Expected Downtime} &= (1\text{-Availability}) \times \text{Operation hour/yr} \\ &= 0.0597 \times 6480 \text{ hours/ yr} \\ &= 387 \text{ hours/ yr} \end{aligned}$$

$$\begin{aligned} \text{Occurrence} &= \text{Expected downtime /MTTR} \\ &= 387 \text{ (hrs/yr) / 9.6 (hr)} \\ &= 40.3 \text{ / year} \end{aligned}$$

$$\begin{aligned} \text{MTBF} &= \text{Operation time / Occurrence} \\ &= 6480 \text{ (hr) / 40.3} \\ &= 160 \text{ hours} \end{aligned}$$

Having looked into the two major sub systems for the NLC, magnet subsystem and the power supply subsystem, the life cycle cost of the whole magnet system can be analyzed.

3.4. Life Cost-Based FMEA

A Life Cost-Based FMEA sheet, as shown in Table 1, was completed for the electromagnet. First, the origin of the failure and the detection stages were identified for each scenario. Failure frequency was assigned with respect to the availability model discussed in section 2.1. Experts in their respected fields gave design, manufacturing, and installation failure frequencies.

Labor cost is obtained using Equation (6) with \$60/hr for labor rate and assumes 2 operators are required to detect and fix the problems. Repairs for an electromagnet failure can cost from a simple replacement of water hose to replacing the whole magnet. Material cost for a simple replacement of hoses can range from \$35 to \$70. Replacing the whole solid wire magnets can range in cost from \$400 to \$2000 and water-cooled magnets can range from \$4000 to \$30,000 depending on the size of the magnet. Power supply repairs usually only require the electronic boards to be switched and parts cost for boards range from \$300 to \$700 depending on the size.

SLAC estimates the lost opportunity due to shutdown to be anywhere between \$10,000 and \$50,000 per hour for the NLC. \$10K is estimated if only direct labor costs are considered, \$25K when direct labor and wasted energy costs are considered, and \$50K when the cost of building the NLC is amortized over a 30-year period in addition to the labor and energy cost. Thus, the overall opportunity cost was calculated for all 3 values.

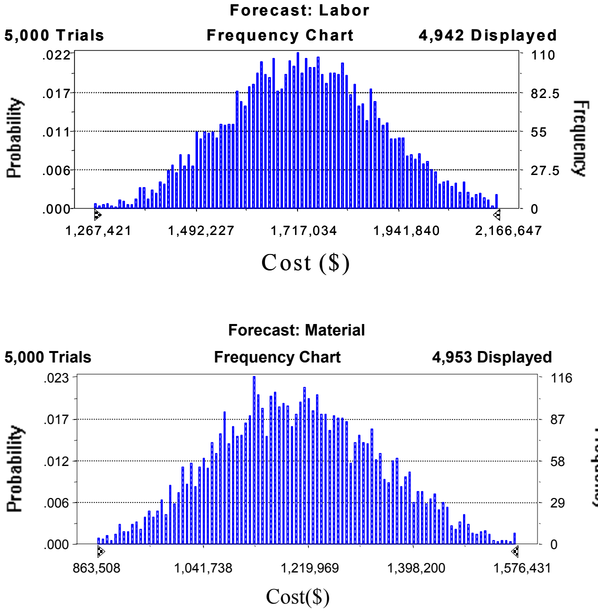

Figure 2. Monte Carlo Simulation of Labor and Material Cost for Electromagnet

A Monte Carlo simulation is applied to the Life Cost-Based FMEA to consider the sensitivity of variables associated to failure cost: frequency, detection time, fixing time, delay time, and parts cost. Figure 2 shows result of the simulation for labor and material costs. A 30 year predicted failure cost for the electromagnet is summarized in Table 8. As shown it the table, opportunity cost can be 30 to 150 times greater than the labor and material cost.

Table 8. Predicted Life Cycle Failure Cost of Electromagnets for the NLC for 30 years

		Correctors			Water Cooled			Electro Magnet		
		Probability			Probability			Probability		
		5%	50%	95%	5%	50%	95%	5%	50%	95%
Labor Cost		$0.300	$0.395	$0.532	$1.200	$1.490	$1.760	$1.500	$1.885	$2.292
Material Cost		$0.065	$0.082	$0.102	$0.900	$1.120	$1.360	$0.965	$1.202	$1.462
Sub Total		**$0.37**	**$0.48**	**$0.63**	**$2.10**	**$2.61**	**$3.12**	**$2.465**	**$3.087**	**$3.754**
	$10k	$6.0	$7.8	$9.7	$72	$90	$109	$78.0	$97.8	$118.7
Opportunity Cost	$25k	$15.0	$19.7	$24.2	$175	$225	$272	$190.0	$244.7	$296.2
	$50k	$30.0	$38.0	$48.0	$350	$450	$543	$380.0	$488.0	$591.0

Units: Million

The estimated failure cost for the system of power supplies is summarized in Table 9. As predicted in Table 7, the availability of large power supplies is pretty low, 0.938. Thus, redundancy is assumed for the large power supplies to meet the availability goal. Material and labor failure cost for large power supplies is still quite high because the power supply electric boards have to be replaced regardless the shutdown of the accelerator.

Table 9. Life Cycle Failure Cost of Power Supply for 30yr

		Small	Large	Total
Labor Cost		$ 0.39	$ 1.90	$ 2.29
Material Cost		$ 0.92	$ 7.20	$ 8.12
Sub Total		$ 1.31	$ 9.10	$ 10.41
	$10K	$ 23	$ 6	$ 29
Opportunity Cost	$25K	$ 59	$ 15	$ 74
	$50K	$ 117	$ 30	$ 147

Units: Million

The magnet system requires the electromagnets and power subsystem to both be working. Thus, the life cycle failure cost of the subsystem is the sum of electromagnet and power supply failure cost as shown in Table 10. The actual labor and material cost is a small fraction of what the total opportunity cost might be, even using the lowest opportunity cost per hour, $10K/hour.

Table 10. Life Cycle Failure Cost of Electromagnet System

		Failure Cost
Labor Cost		$4.2M
Material Cost		$9.3M
Sub Total		$13.5M
	$10K	$126.8M
Opportunity Cost	$25K	$318.2M
	$50K	$635M

4. DISCUSSION

As derived in the previous section, availability for the electromagnet system falls short of the target goal of 97.5%. To increase the availability of the water-cooled magnets for the NLC, two measures can be taken: reduce MTTR or increase the reliability of the electromagnets. The average MTTR for water-cooled electromagnet is 10 hours and 2 hours for the solid wire magnets as determined from empirical data at SLAC. Referring to Table 3, the average fixing time for insulation and water leak is 8 to 10 hours.

Figure 3 shows the top four failure costs with respect to its root cause. Opportunity cost of $25,000 per hour was used for this analysis. Water leak has the highest failure cost with a total cost of over one hundred million dollars with a 50% probability. Thermal, radiation, and mechanical are the following high cost failures. Thus, we will investigate and suggest recommendations regarding water leak failures.

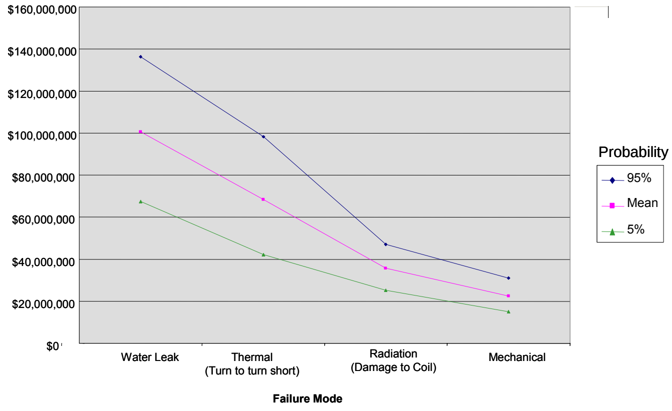

Figure 3. Top Failure Costs

The time to fix water leak failures can range anywhere from as little as one hour to as much as 32 hours. A bad water leak can take up to 32 hours to dry out the magnets. Design

Table 11. Predicted Life Cycle Failure Cost of Electromagnets with 50% Reduction in Fixing Time

		Correctors			Water Cooled			Electro Magnet		
		Probability			Probability			Probability		
		5%	50%	95%	5%	50%	95%	5%	50%	95%
Labor Cost		$0.300	$0.395	$0.532	$0.600	$0.880	$1.150	$0.900	$1.275	$1.682
Material Cost		$0.065	$0.082	$0.102	$0.900	$1.120	$1.360	$0.965	$1.202	$1.462
Sub Total		**$0.37**	**$0.48**	**$0.63**	**$1.50**	**$2.00**	**$2.51**	**$1.865**	**$2.477**	**$3.144**
Opportunity Cost	$10k	$6.0	$7.8	$9.7	$43	$52	$67	$49.1	$59.8	$76.2
	$25k	$15.0	$19.7	$24.2	$103	$130	$160	$118.0	$149.7	$184.2
	$50k	$30.0	$38.0	$48.0	$206	$260	$320	$236.0	$298.0	$368.0

Units: Million

improvements to shorten the fixing time of replacing the fittings and coils will significantly decrease MTTF for water leaks. An average 50% reduction in MTTR, from 10 hours to 5 hours, for water-cooled electromagnets will increase the availability of magnets to 97.6% as shown in the following equations:

$$A_{1M} = \frac{MTTF}{MTTF + MTTR} = \frac{1{,}078{,}216}{1{,}078{,}221} = 0.9999953$$

$$A_{4965\,M} = (0.9999953)^{4965} = 0.977$$

$$A_{MSys} = A_{WM} \times A_{SM} = 0.977 \times 0.999 = 0.976$$

$A_{4965\,M}$: Availability of 4965 magnets
A_{MSys} : Availability of the magnet system

A summary of the Monte Carlo simulation of the Life Cost-Based FMEA with improved MTTR of 5 hours for failures that occur during operation period is shown in Table 11. A six hundred thousand dollar savings can be expected over 30 years in labor and material costs if the fixing time is reduced by 50%. However, the incentive to reduce fixing time is more evident in opportunity cost. Comparing tables 8 and 11, a 40% reduction in opportunity cost can be expected through reducing the time spent on fixing electromagnets.

5. CONCLUSIONS

This paper demonstrated the systematic use of empirical data in performing Life Cost-Based FMEA and how it can improve the reliability and life cycle cost of complex systems such as a linear particle collider. Our previous investigation (Rhee, 2002) had a limited scope in applying the Life Cost-Based FMEA to a simple component.

Life Cost-Based FMEA aids not only design improvements and concept selection, but it also allows one to improve and plan preventive and scheduled maintenance of components. Thus, Life Cost-Based FMEA has three main benefits: estimation of life-cycle cost, FMEA, and Service Mode Analysis (SMA). The proposed method inherently captures a system's life-cycle costs related to component failures during design, manufacturing, installation, and operation. Designers can readily incorporate the changes in the model to estimate an improved life cycle cost. The root causes directs designers to focus their efforts on problem systems, components, and processes.

Complex systems usually have a set target availability. One means to achieve the target is to increase all subsystems reliabilities. However, guaranteeing higher reliability often incurs cost increases. Another solution is to schedule preventive. Our proposed methodology maps allows comparisons of different availability enhancement measures and trace analysis in terms of cost, a widely accepted measure of risk.

Life Cost-Based FMEA can also provide a fair comparison between competing designs of subsytems. The case study presented in this paper considered only the currently used magnet technology. The proposed methodology may not simply extrapolate to new and/or unproven technology, because empirical or expert knowledge may not be available. Thus, future research lies in estimating uncertainty variables (e.g., frequency, detection time, fixing time, and delay time) using available component data, and extrapolating them to higher subsystem levels. Hybrid use of empirical and analytical data will present significant new challenges.

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