Using Lifecycle Cost (LCC) Analysis to Evaluate Reliability Alternatives

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Introduction

You might ask yourself why a discussion of reliability would include information on lifecycle cost analysis. Stated in the simplest terms possible, the cost of reliable components, equipment and systems is greater than ones that are not reliable and you cannot justify the cost of features and components needed to provide a reliable asset based only on the risks of failure you will experience today or tomorrow. You need a process for comparing reliability-related costs that takes credit for the value of failures that are avoided long into the future. That system is Lifecycle Cost analysis or LCC.

Truly reliable systems require robust components and redundancy that are more expensive than those elements in unreliable systems. In order to justify the additional spending you will need to employ lifecycle cost analysis to fully understand the present value of costs that may occur long into the future or, at least, for the period you will own the asset. Financial analysts and managers need to see an "apples-to-apples" comparison of alternatives to be convinced they are making the best choice.

While the inherent value of reliability seems obvious to technically minded people, it does not seem to be so apparent to many others. You need to explain to them in financial terms they understand.

Lifecycle cost analysis provides both the structure and the rigor needed to satisfy even the most difficult accountant. When the practice of using lifecycle cost analysis becomes second nature for individuals and organizations, development of assets with the proper level of reliability to fulfill their business model will also become automatic. LCC will make it clear that unreliability and unavailability is unacceptable.

High Level Description of LCC Analysis

Over the life of an asset there are a variety of choices that can be made. One alternative may include more preventive costs and fewer costs associated with failures. Another alternative may include fewer preventive cost but more costs associated with failures resulting from poor reliability. Other alternatives may include choosing to use more robust components that do not require additional preventive maintenance nor experience unexpected failures. It is possible to model alternatives and select the one that affords the most favorable return on investments or best fit a company's investment model.

Unfortunately all of the costs in the various alternatives do not occur at the same time. As a result, it is necessary to convert all future cost to one single point in time. All cost other than those occurring at the present time must be converted to their present values by multiplying the cost by the PV factor that is appropriate for the time the expense occurs and for the current interest rate. Use of the proper interest rate insures that all future expenses are measured using the same standard as other investment opportunities.

An important element of lifecycle cost analysis is that it must be comprehensive. All costs associated with prevention or immunity must be balanced against all costs associated with unreliability or of the future failures being prevented.

In some instances the cost of unreliability may be quite expensive and may include cost of repair as well as lost production and a variety of other impacts that would not be considered using a more superficial analysis. A meaningful assessment of the cost of unreliability and therefore of the amounts that can be prudently spent to avoid those costs requires a comprehensive and accurate portrayal of all costs and the risks they produce.

Present Value Analysis of Cost Elements over the Life of an Asset

Let's begin this discussion with a simple equation. To arrive at the present value of a future cost divide the future costs by:

$$(1+ i)^t$$

where *'i'* is the interest rate used for alternative investment opportunities and t is the number of compounding periods at that investment rate. It is important to state the interest rate that has been used when performing an analysis, so if that rate is incorrect, the analysis can be repeated using a rate that others feel is more appropriate.

For example, let's assume you would like for me to loan you $1000 and you would like to repay me next year. The other investment opportunities available to me pay 10% per year interest. How much would you need to pay me next year? The answer would be $1100. In other words, the present value of $1100 next year would be $1000 in the current year.

Now let's assume that you have a promissory note for $5000 to be paid five years in the future, but you need some money now. How much should I be willing to give you now in exchange for the $5000 note to be paid five years in the future? Again, my other alternatives provide a 10% return.

Present Value = \$5000 / $(1 + 10\%)^5$ = \$5000 / 1.61 = \$3104.

In other words, if I gave you $3104 today, you would have to pay me $5000, five years from today.

Now let's go through an example of how this applies to reliability.

Assume that you plan to purchase a new asset. You have two choices: choice 'A' has some features that will prevent a failure five years in the future and that failure has a cost of $5000, choice 'B' does not have that feature.

The initial costs of choice 'A' is $7000 and the initial cost of choice 'B' is $5000. Choice 'B' also has a future cost of the failure to consider. Based on earlier calculations, the present value of a future cost of

$5000 that will occur five years in the future is $3104. Therefore the total present cost of alternative 'B' is $8104. In other words, alternative 'B' is somewhat more expensive than alternative 'A'.

Let's take another example. Let's assume there is only one choice for an asset, so the initial cost is the same in either case. The alternatives we can consider are the cost of preventive maintenance. Let's assume that the cost of the failure remains the same as in the last example. In this case, the alternatives are the choice of performing some preventive maintenance before the failure occurs or allowing the failure to occur. Assume that the preventive maintenance could be accomplished in year four and would cost $4000. Returning to the present value calculation, the present cost of the alternative using maintenance to prevent the failure is $2732. Comparing the present value of the maintenance costs to the present value of the cost of the future failure, it would be less expensive to perform the preventive maintenance than to ignore the maintenance and allow the failure to occur.

The value of performing present value calculations of future cost is that it allows you to compare significantly different lifecycle assumptions and to do so in an equitable manner.

Useful Definitions

As a basis for continuing our discussion to greater depth, it is useful to provide a few definitions for terms that will be used:

Lifecycle cost analysis or LCC – Lifecycle Cost analysis refers to an analysis that considers the total cost of ownership over the life of an asset, also commonly referred to as "cradle to grave" or "womb to tomb".

Present Value or PV – Present value, also known as present discounted value, is the current value of a payment or series of payments made at some date in the future. When using the Present Value calculations to consider alternative investments, it is important to use the appropriate interest rate or "time value of money".

PV factor – A Present Value factor or PV factor is the number by which you can divide a future amount to determine its current value. The PV factor takes into account the alternative interest rate and the number of compounding periods between the current time and the time at which the future amount exists.

Accepted Risk - Mathematically, a risk is the net cost of an event times the likelihood that the event will occur. If you flip a penny there is a 50% likelihood that it will turn up heads and a 50% likelihood that it will turn up tails. If you bet $100 that it will turn up heads and your bet is not against an equal and opposite bet, you have accepted a risk of $50 (or the value of the loss times the likelihood of the occurrence). If you bet $100 it will turn up heads and someone else bets it will turn up tails, your mathematical expectation is zero. You are as likely to win $100 as you are to lose $100.

If you were to accept the first arrangement, you would have accepted the risk. If you would have accepted the second arrange, you off-set your risk with the likelihood of winning an equal amount.

While the results will not even out in a single coin flip, over the long-term, the losses and wins should balance and there will be no net loss or gain. In business, the objective is to avoid accepting risks that you cannot afford to lose and for most risks finding some way to balance the scales.

In the business of reliability, you will balance the scales by eliminating the likelihood of the possible loss. Doing so is not free. The objective is to spend an equal or less amount to eliminate the failures than the failures would have cost if left to occur.

Immunity - When a person is immunized by getting a shot or injection, they have an immunity to a specific kind of disease or illness. In much the same way, it is possible to make a device immune to a specific form of deterioration by changing the materials from which it is constructed or by changing the design in a way that makes it no longer susceptible to deterioration. When it is decided to use immunity as a way to eliminate failures and improve reliability, the solution typically has a higher initial cost, but both eliminates on-going failures and does not require the burden of on-going Predictive Maintenance and Preventive Maintenance.

Prevention - Like immunity, prevention can be used to improve reliability only without the higher initial cost of an improved component but with the requirement for on-going Predictive Maintenance and Preventive Maintenance for the remainder of the asset life.

Lifecycle Costs - Lifecycle costs are all the costs that will be experienced for the remainder of the life of an asset. When comparing the lifecycle costs associated with reliability there are typically three cost patterns to be considered:

- The costs associated with the "do nothing" case are typically all the costs associated with failures throughout the life of the asset. In many instances the most significant cost of accepting the risks associated with the "do nothing" case are the costs of lost production or the total cost associated with the asset being unavailable during failure and repair of a specific component being analyzed. In addition to the cost of loss production, the "do nothing" case must include the cost of repair being made on an emergency and unexpected basis, frequently without planning or scheduling and possibly including a period of waiting to obtain parts and additional repair costs due to peripheral damages.
- The costs associated with the "immunity" case are the costs of replacing the failing component with one that is immune to the Failure Mechanism (also called deterioration or damage mechanism). This is typically both a larger cost than the component being replaced and one that must be paid immediately thus not reduced by application of a Present Value factor to some future amount.
- The costs associated with "prevention" are the costs of performing Predictive Maintenance on a near-continuous basis then, when deterioration is found and the end-of-life is near, triggering Preventive Maintenance which will replace deteriorated parts before a failure can occur. Replacement of a component before it fails infers that a portion of the useful life of the component is sacrificed, but there are no peripheral damages or added costs of inefficiency due to the work being unplanned and unscheduled.

Cost Elements for Maintenance and Reliability

For the sake of simplicity, let's assume that you were able to purchase an asset that was perfectly reliable. After paying the initial cost, there would be no costs of unreliability or failure over its entire life. To determine the amount you should be willing to pay for reliability as part of the initial cost you would need to identify the cost of all failures later in life that are being avoided.

One way to identify all the cost of unreliability would be to perform a three-step analysis:

1. The first step of the analysis would be to perform a Reliability Block Diagram (RBD) analysis of a typical system that displays the failures expected of a system with normal or non-perfect reliability.
2. Using the failure modes identified in the RBD analysis, perform a Failure Modes and Effects Analysis (FMEA) that describes the effects of all those failure modes. Once the effects have been described, it would be necessary to “monetize” them or determine how much each of them would cost in dollars.
3. The last step is to bring the costs of all future events forward to the present value by multiplying them the appropriate PV factor.

Finally adding up all the present values of all future events will show the total present value of all future failures. Adding the sum of the present values of all future failures events to the cost of the system with typical reliability will provide the value of a system with perfect reliability.

Now, let's take a second approach at quantifying the cost of reliability. In this analysis, rather than determining the value of the system that is initially designed and built to be perfectly reliable, we will assume that we will purchase a system with typical reliability and we will perform prevention over its entire lifespan to provide the same level of perfect reliability as was provided by the perfectly reliable system.

In this form of analysis, we will need to use the results of the RBD analysis to once again identify the failure events and their timing. Here we will apply Reliability Centered Maintenance (RCM) analysis to identify a program of predictive and preventive tasks that will be conducted over the life of the asset to keep it perfectly reliable.

Once again we will need to use the appropriate PV factors to bring the cost of all those future tasks forward to the present time. Summing up the present value of all future predictive and preventive maintenance tasks and adding them to the current cost of a typical, non-perfectly reliable system will provide the cost of this alternative.

Finally, we will use the analysis that has been performed for other alternatives to identify the components that need to be made more robust to avoid all those failures. In addition to the base cost of the asset with typical reliability, the cost of selecting and installing more robust components that will eliminate all failures, will be added.

The several analyses we have performed here have provided us with three alternatives to consider:

1. The first alternative is one in which a typically reliable system is purchased and no particular care or prevention is exercised. In this case the initial cost is small but the costs of failures over the life of the asset are significant.
2. The second alternative is one in which a typically reliable asset is purchased and all necessary prevention is applied to avoid failures at the cost of more maintenance.
3. The third alternative is a perfectly reliable system. This system has replaced weak components with ones that are more robust and has the highest initial cost but the lowest cost over the remaining life.

This analysis is useful because it compares values of various assets versus various prevention schemes that cover the entire life of the asset. Using these alternatives, the long-term owner is being offered assets at various initial costs that display different failure rates and maintenance costs over the life of the asset.

While the analysis described and the assumption of a “perfectly reliable” system is not realistic, it does provide the tools needed to compare various strategies. So rather than having a perfectly reliable system or a preventive maintenance program that is perfectly effective, you will likely compare real-life alternatives that have some of each:

- The initial asset isn't perfectly reliable.
- Your program of prevention will not be perfect.
- All failures will neither be perfectly avoided nor perfectly allowed to occur over the life of the system.

So, in reality, your lifecycle analysis will compare alternatives that have some of each. In some instances the most cost-effective alternative is to install a robust component that will not fail. In some instances, it is best to perform predictive and preventive maintenance to avoid failures. And in some instances it is most cost effective to simply "run to failure". Your objective is to select the alternative that provides the greatest value at the least cost when viewed from the entire lifecycle of the asset. To some extent, rather than depending on perfection, the real-life total cost of ownership depends on luck of having the end of life occur at times when the asset would be down for other reasons so there is no cost of loss production.

A Comprehensive List of Lifecycle Costs that Should be Considered

Smart companies strive to eliminate all forms of failures and operate their assets in the most reliable manner with the highest availability. Those companies realize that in addition to the obvious and easily quantified costs resulting from poor reliability, there are a number of hidden costs. Many of these costs are concealed by the fact that they are either difficult to extract from financial systems or it is difficult to allocate the portion of total losses that should be directly attributed to specific failures. The fact they are difficult to quantify does not mean they should be ignored or that they do not exist.

Smart companies realize that the only truly effective way to rid themselves of these costs is to eliminate the unreliability and resulting unavailability.

The following is a more comprehensive list of total costs that can be used to justify reliability improvements if they can be properly extracted from financial systems and fairly allocated.

Initial Cost - The initial cost of a component known to be reliable includes several cost elements not included in the cost of components with uncertain reliability. First there is the cost of development and testing needed to determine the device will survive certain failure mechanisms and activities needed to ensure the component is constructed to the required robustness and quality. Second, the device is typically constructed using materials that are marginally more expensive than less reliable components.

Cost of DFR - The DFR is an abbreviation for Design For Reliability. In most instances, sub-components, components, equipment, systems and assets are designed only to provide a specific form of functionality. The process of designing any level of device to operate at a specific level of Reliability and Availability is a separate activity and is no way guaranteed by the conventional design process. Performing DFR as a part of the overall design process costs slightly more than conventional functional design and requires slightly longer to complete. The added time can be minimized by performing concurrent engineering or timing DFR to coincide with steps of the conventional design.

Cost of Product Development - The cost of Product Development for a reliable product is somewhat greater than the cost of Product Development for a product for which no specific level of reliability, availability or useful life is guaranteed. The difference can be described using an example. A product can be proven to be functional by simply using the initial example to perform the intended function a number of times until the "bugs" have been worked out. Proving that the same device will perform at a specific reliability, availability and useful life requires the application of an accelerated testing program covering the number of operating cycles the device is expected to experience over its entire lifecycle.

Maintenance Cost - When we discuss maintenance costs, we are referring to all forms of maintenance needed to ensure both the functionality of an asset and the desired level of reliability and availability. These costs include: Periodic Maintenance (like oil and filter changes), Predictive Maintenance (like checking for the presence of or the status of deterioration), Preventive Maintenance (or steps taken to return an asset to good as new condition when deterioration has been found), Corrective Maintenance (or steps needed to repair after a failure), Overhauls or Turnarounds (or general reconditioning needed to regularly restore aging assets to much the same functionality and serviceability it had when new).

Predictive Maintenance Cost - Predictive Maintenance is the collection of activities completed to identify the presence of deterioration, determine the rate of deterioration, identify the time the deterioration will result in a failure and the triggering of Preventive Maintenance.

Preventive Maintenance Cost - Preventive Maintenance is the timely replacement or repair of deteriorated elements to return them to "good as new" condition and to do so before a failure can occur.

Breakdown or Failure Costs - When neither immunity nor prevention has been provided and an asset is allowed to fail, there will be a number of costs associated with the Breakdown or failure. They include but are not limited to:

- The cost of downtime for lost production or revenues.
- The cost of direct repairs.
- The cost of peripheral, collateral or indirect repairs. (For instance If an engine runs to failure and the block is damaged as well as valves or connecting rods, the block and all associated costs are part of the cost of the failure.)
- The costs of inefficiencies associated with unplanned, unscheduled emergency repairs. Studies have shown that unplanned and unscheduled maintenance can cost four times the resources, take four times the time and can produce four times the number of safety related events as do planned and scheduled maintenance activities.
- The costs of slowdowns to other assets that are linked to the failed asset.

Cost of Lost Production - While at times it is difficult to relate the costs of lost production directly to the failure of a small sub-component or component, it is important to describe this relationship as closely as possible. These costs can make up as much as 90% of the losses and therefore justify even fairly costly steps and activities needed to avoid failures.

Cost of Quality - The production of off-spec products can occur both during deterioration and after failures are evident. When component OEMs do not adequately monitor the quality of their products, the poor products they produce can result in poor quality for their customers for long periods of time. When failures occur, it is possible for the owner to produce off-spec products while a component is failing, during the failure and after repairs but before smooth operation has been restored.

Safety and Environmental Costs - Depending on the severity and extent of a failure, it is possible that unsafe conditions or environmental issues may result. Depending on the severity, the failure event can result in penalties or fines that significantly add to the cost of the failure both directly and as a result of damaged reputation.

Miscellaneous Costs - Some failure events trigger a series of costs far greater than simple repairs and related downtime. It is useful to consider these costs when deciding how much can be spent on immunity or prevention. A few exceptional costs follow:

> - *Organizational Costs* - For exceptionally large scale or frequent repairs, the size and expertise present in an organization must be enhanced when compared to that of an enterprise using reliable assets. Organizations typically "morph" into larger and more expensive organizations over time so the difference may not be clearly recognized unless carefully compared to those with better reliability performance.

- *Costs of Interruptions* - Again, while it may not be recognized without some study, plants and companies that experience frequent or extensive reliability-related interruptions may experience added costs because of the interruptions. Interruptions may delay projects or programs that would have otherwise provide revenues much earlier.

- *Spare Parts Costs* - In addition to the direct cost of spare parts needed because of marginal reliability, there are added invisible costs, like shelf life, taxes, and obsolescence of spare parts.

- *Warehousing and Inventory Costs* - Where there are parts there are also the costs associated with warehousing including personnel, facility costs, inventory costs, etc. As the need for spare parts grow, so do the costs of warehousing and inventory management.

A Typical LCC Spreadsheet using Excel

The simplest and easiest way to perform a LCC comparison is by using an Excel spreadsheet. In addition to providing a tool for identifying all the possible alternatives and arranging the various costs in the proper year of their occurrence, the Excel spreadsheet contains algorithms capable of determining the PV factor that must applied to each future cost to determine their Present Value.

The following is an example of an Excel spreadsheet comparing three alternatives: the "do nothing" case, a cased based on installing a new component that is partially immune to failures (but for which a smaller number of failures continue to occur) and a reliability improvement approach based on prevention provided by a regimen of predictive and preventive maintenance.

Several points should be made before reviewing the spreadsheet comparison:

- The time value of money or interest rate being used is 10%. (The percentage used should be the same percent being used by your financial organization to compare investment opportunities.)
- The useful life being used is 20-years.
- The new component intended to provide immunity reduces the number of failures to one-fifth of the current frequency of failure.
- The current MTBF is 2-years and the new MTBF being provided by the "immune" component is 10-years.
- The cost of Predictive Maintenance continues to occur all of the time and the cost of Preventive Maintenance occurs at the MTBF of the current component but it replaces the failing component in a planned and scheduled way without the peripheral costs associated with an unexpected breakdown. (Note that planned and schedule replacement will cost one-fourth as much as unplanned and unscheduled maintenance, it will take one-fourth as long and likely result in one-fourth the number of safety related incidence as unplanned and unscheduled work.)
- While other maintenance costs do exist, it is assumed that they will be the same for all three alternatives, therefore do not need to be compared.

Lifecycle Cost Comparison for Three Alternatives for 20-Year life at 10% Time Value of Money

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Present Value of 20 Year Lifecycle Costs
Do-Nothing Case																						
Initial Investment																						
Predictive Maintenance																						
Preventive Maintenance																						
Failure Costs			25000		25000		25000		25000		25000		25000		25000		25000		25000		25000	
Misc Costs		2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	
Total Cost	0	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	2000	27000	$107,617.34
Immunity Case																						
Initial Investment	50000																					
Predictive Maintenance																						
Preventive Maintenance																						
Lost Production											25000										25000	
Misc Costs											2000										2000	
Total Cost	50000	0	0	0	0	0	0	0	0	0	27000	0	0	0	0	0	0	0	0	0	27000	$58,566.41
Prevention Case																						
Initial Investment																						
Predictive Maintenance		3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	
Preventive Maintenance			6000		6000		6000		6000		6000		6000		6000		6000		6000		6000	
Lost Production																						
Misc Costs																						
Total Cost	0	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	3600	9600	$49,975.72
Best Alternative																						$49,975.72

Note that the alternative using Predictive and Preventive maintenance is the least costly. That alternative has the characteristic of improving reliability while avoiding any significant initial costs. The possible disadvantage of increased predictive maintenance and preventive maintenance is that it adds to the burden being placed on the maintenance department.

It should be noted that when an OEM sells a product requiring a great amount of predictive and preventive maintenance, he has managed to shift the cost and responsibility of failures from himself to the permanent owner of the asset.

Identifying and Quantifying Impact of Accepted Risks

We all recall the children's story about the chicken who went about telling others that the sky was falling or the fairytale about the boy who called wolf when there was no wolf.

These stories pointed out the importance of credibility when issuing warnings. Much of the effectiveness of lifecycle cost analysis, in specific, and reliability engineering, in general, depends on the credibility of the reliability engineer.

When the reliability engineer identifies a risk of failure and offers a solution that will eliminate the cause of the risk, people must accept the validity of the engineer’s proposal. If they do not, they will not approve the expenditure of resources and the risk will continue to exist.

In simple but precise terms:

Risk = Impact x Likelihood

In this equation, the impact is the total cost of all elements of an event caused by a failure. The possible failure modes of a component are the triggers that produce the impact.

In order to make an accurate comparison with other costs, it is necessary to monetize the value of failures and/or the risk of failures. While the risk of a catastrophic fire or explosion may be sufficient to convince many individuals that some form of prevention is needed, it is not sufficient to justify the required investments in the minds of business managers. It is important to justify both "if" investments are needed and "how large" the investment should be.

As an example, let's choose a fairly dramatic event. Several years ago I heard of a situation in which the identifying marks on an I-beam were too deeply stamped into its web very near the center of the span. The beam was used to support a country road bridge in the central part of the United States. The improperly applied marking made the beam susceptible to fatigue and after a large number of cycles a crack formed and ran all the way through the beam. The failure mode, Support Beam – Cracked Through, caused the bridge to fail. The cost of that failure included the following elements:

- The cost of a new bridge and removing the failed bridge
- The cost of rerouting traffic through the detour

- The cost of delaying whatever form of traffic occurred in the path under the bridge (for example River barge, railroad or on the road)

(In this case, there were no fatalities but in performing an analysis of possible impacts in other instances, one might include that possibility.)

In the risk equation, the term likelihood refers to the statistical likelihood or probability the event producing the impact will occur during any specific period of time. As you might expect, the likelihood of failure will vary based on the component being used and the period of time under consideration. The likelihood of failure may follow any of a number of forms over the life of the component. For instance, the likelihood of failure of many components follows the form of the bathtub curve: beginning with the relatively high likelihood of infantile failure, followed by a long period of low likelihood of random failure, ending with an increased likelihood of failure at the end of life.

For the specific example of the bridge beam with improperly applied markings, the likelihood of failure for similarly marked beams at the end of a large number fatigue cycles was quite high. This was not true if the markings were applied to a proper depth or if markings were applied well off-center. Also, the number of fatigue cycles required more than 50 years to occur. So the likelihood of failure did not begin to increase until the age neared the 50-year point.

So in this case, if the reliability engineer wishes to make a credible warning, he would need to confine his recommendations:

1. To bridges with beams having markings with a depth equal or greater than a specific value and having been applied within a specific distance of the centerline of the beam.
2. The recommended solution would only need to be applied to instances where the bridge was more than, say, 45 years of age. (The five-year gap is applied to account for differences beyond the accuracy of calculations.)

As a safety measure, bridges could be visually inspected for beams containing such markings. If instances with such markings were found to exist and there were more than 45 years old, the areas around the markings could be inspected for incipient cracking or replaced. In cases where cracks were found, the bridges could be taken out of service and the beams strengthened.

In the example, the risk of failure to bridges with improperly marked beams is one that truly exists. When the risk has been identified, analysed and a recommendation made, if the recommended action is taken, the risk is not an accepted risk. If no action is taken, the risk is an accepted risk. By clearly articulating the likelihood of failure and creating a palatable solution, the reliability engineer has made it easy for resource managers to find ways to eliminate the risk rather than ignoring and accepting them.

While not as dramatic as this example, most reliability related failures are similar to the example. The known failure modes for the asset components create a likelihood of failure. Each failure mode will produce an impact. The likelihood of that failure mode and the resulting impact can be eliminated by some prudent action.

The reliability engineer can create a justification for taking action by clearly describing the risk and by identifying an economically acceptable alternative solution. Rather than helping, it typically hurts to exaggerate:

- The impact of failure
- The likelihood of its occurrence
- The efforts needed to mitigate it

Quantifying the Overall Impact of a Failure

Effects of almost any failure can be taken to an extreme or they can be understated.

In the last section, I described a failure mode that affected a bridge beam. It so happened that this beam was part of a bridge that was out in the country and it passed over the dormant railroad track. When it failed, no person was injured.

In preparing the recommendation to inspect bridges for improperly applied markings, the engineer preparing the justification could have assumed that all future failures would have occurred as this one did. Or he could have assumed that the next bridge failure would occur in the middle of the city, in the middle of rush hour traffic, when the bridge was loaded with minivans all carrying large families many of whom were small children. The bleak picture would bring tears to your eyes.

In reality, the failed beam was a specific span and had specific load-bearing capability. This beam was most commonly used in railroad trestles by one specific railroad. While the likely impact of failure would typically be somewhat more severe than the first incident, it was possible to identify a fairly realistic outcome that had only a moderate impact.

Again, exaggeration doesn't help. They lead to loss of credibility.

Once you have determined that an event is likely and should be included in the lifecycle cost analysis being performed, it is important to include the cost of all likely elements.

For instance, in the case of the bridge example, if the bridge had collapsed it would have been necessary to remove the failed bridge. On many occasions, the awkwardness of removing structurally unstable components introduces a significant expense. Also, in the initial case, only one avenue of traffic was interrupted. In most cases, it would have been two: the one going over the bridge and another passing under it. When performing lifecycle cost analysis of the reliability of bridge alternatives, including all the assumptions described in the last few sentences would not be exaggerations. Once you have quantified a realistic likelihood of failure at some time after the 45 year point, you should multiply that likelihood by the total cost of all these impacts to determine the total risk. Also, assuming that the improper markings exist on a number of bridge beams, the total risk is the sum of all instances where that risk exists.

Again, while the failure of the bridge beam and the bridge are larger and more profound than most reliability failures you will analyze, the philosophy remains the same. Do your best to provide an accurate estimate of likelihood and a realistic quantification of impact and your recommendations are likely to be well received.

Monetizing or changing the impact of a failure into a specific dollar amount is an important step in quantifying the impact. Clearly no two people view the impact of a failure in the same way without stating the impact in dollars. Modern financial tracking systems are helpful in identifying the overall costs of any event because they allow the differences between costs and returns to be compared between two equivalent periods of time, one with a failure and one without.

In many instances companies make accommodations for unexpected outages by building a backlog of products that can be drawn upon during interruptions. In these cases, it is important to properly evaluate the impact of the outage had the backlog of product not been available. This is an important consideration when considering the likelihood of a reliability related event during the period immediately following a planned outage or major overhaul. These periods tend to create the "perfect storm" for reliability related failures:

- The backlog inventory has been consumed during the outage.
- The asset is unstable and more susceptible to failures during re-start.
- The entire crew and management are tired after the long hours associated with the outage.
- The typical inventory of spare parts were consumed during the outage so it is more likely that replacement parts would require a wait.

It is helpful to consider these unusual although possible situations when evaluating weak or marginal components.

Quantifying the Likelihood of a Failure

While determining the impact of a failure event is fairly straight-forward, evaluating the likelihood of the event is not as simple.

There are two ways to include the cost of failures in your lifecycle cost analysis. One is to simply place the cost of the failure at the MTBF of the component causing the event. In other words, if a component has a MTBF of 2-years and the cost of the failure event is $25,000, a $25,000 debit can be placed in the LCC spreadsheet every other year.

Another, possibly more accurate way of including the cost impact of failures is to include the value of the risk of failure during each and every period of the analysis.

Since Risk equals Impact times Likelihood, the value of risk that must be added to each period of the analysis is the cost impact of the failure times the likelihood the event will occur.

To evaluate the likelihood of the failure it is necessary to know both the MTBF of the failing component and the interval over which the risk is being evaluated.

The MTBF is calculated using the following equation.

MTBF = $\sum (T_2 - T_1)$/Number of replacement events

Where T_2 is the time when the component fails and T_1 is the time when the component was installed. The MTBF is the average of the life spans for either a number of consecutive lives or the life spans for a number of the same component installed in other assets.

For our purposes, the MTBF should be calculated in terms of years. Also for our purposes, we are interested in evaluating the risk of failure for one year so the value or the risk can be included in each annual budget. Therefore, in the following equation, we will use t = 1.

$R = e^{-t/MTBF} = e^{-1/MTBF}$

If the MTBF were 3 years, the Reliability, R would be $e^{-.3333...}$

Or R = 71.66% or .7166

Since R + L = 1. where R is reliability and L is likelihood of failure,

L = 1 - R

When MTBF = 3-years and t = 1-year

L = 1 - .7166 = .2834

Or the likelihood of failure is 28.34% for each year.

If the monetized impact of a failure is $100,000, the annual risk would be $28,340. When using this approach, the risk is included in each year during the life of the asset rather than just the years when the end of the MTBF of the asset occurs.

Example LCC of an Individual Element

For the sake of completeness, let’s describe the way lifecycle cost analysis would be used with respect to a single element or component of a system.

Generally speaking, when you apply life cycle cost analysis, you'll have two or more alternatives. For now we will assume there are only two alternatives. Let's also assume that the alternatives have some significant differences in their usable lives and the maintenance they require.

A common comparison is the choice between using a carbon steel pressure vessel in a process plant or using one made of an alloy. Let's begin by describing the lifecycle of the carbon steel alternative.

- The lifecycle begins with the purchase of the carbon steel vessel. In the case of the carbon steel vessel, the vessel might cost 40% less than one made using alloy materials.
- We will assume that carbon steel corrodes in this service. For the sake of this discussion, we will assume the half-life is less than 10 years so the service is corrosive and the vessel must be inspected every time the plant is down for turnaround. Let's assume that turnarounds are conducted every four years. This introduces added maintenance costs for blinding, flushing, cleaning, scaffolding and inspection every four years. For simplicity we will assume that the vessel has only uniform corrosion, so rather than localized repairs the only repair cost will be associated with replacement of the vessel every 20 years or sooner.
- Let's assume that the service this vessel has been used in is toxic in nature so specialized and costly procedures are needed to dispose of the vessel once it is removed.
- Let's also assume that once during the life of this plant, it is common to have a runaway condition during which carbon steel components are likely to be damaged to the point of leakage. Assuming that if the carbon steel vessel is selected, it would be the only carbon steel component in the plant and it would be the sole cause of the resulting plant outage while the replacement vessel is being fabricated and installed. We assume that during a 30 year life this would happen at the 15 year point and the time to fabricate a replacement would be six weeks, all the while the plant will be down.

The cost elements we need to include in the lifecycle cost analysis for this component are as follows:

1. Initial cost of the carbon steel vessel.
2. Inspections at the 4, 8, 12, 16, 20, 24 and 28 year points.
3. A runaway failure, extended outage, vessel replacement and environmental handling of the removed vessel at the 15 year point.
4. Since the vessel has been assumed to be replaced at the 15 year point because of the runaway, it will not need to be replaced at the 20 year point.
5. Since the economic life of the asset is 30 years, we will assume only one runaway during the life of the asset.

For each of the elements described above, the current costs will need to be converted to a present value using the appropriate PV factor for the year when the expenditure occurs.

Now let's consider the alloy vessel. In this case, there are fewer cost elements to consider. They are:

1. The initial cost of the alloy vessel would be 67% more than the carbon steel vessel.
2. While the half-life is more than 10 years, the maximum interval between inspections is 10 years. Assuming that the plant has turnarounds on a four-year cycle to avoid going beyond the inspection interval limits, this vessel must have an internal inspections during the following turnarounds: 8 year, 16 year, and 24 year.
3. Assume that alloy does not corrode in this service so the vessel does not have to be replaced at any point.

4. Assume that this vessel is not susceptible to damage during runaway events, so it does not have to be replaced when they occur. The resulting outage also does not occur.

As with carbon steel vessel, all costs need to be brought forward using the appropriate PV factor. It is important to keep in mind that all costs occurring after the 30 year life do not affect the comparison.

In this comparison, if the cost of additional inspections, the cost of replacement and plant downtime when the carbon steel vessel fails far outweigh the 67% premium in initial cost of the alloy vessel. The alloy vessel would make a better choice. Frequently in situations like the one described, analysts expand the total cost (of the vessel failure and plant outage) to include intangibles due to uncontrollable events during the plant operation and outage. The value of intangibles would further encourage the choice of the alloy alternative.

Comprehensive LCC of an Asset or Fleet

Earlier we discussed the choice between alternatives involving a single component in a plant. While that was a useful example to help understand the value of lifecycle cost analysis, it is more common to consider how lifecycle cost analysis pertains to an entire asset or to large fleets of assets.

For instance, it would be unusual to consider replacing only one vessel in an all alloy plant with a carbon steel vessel. The more typical analysis would be one in which a large number of components within a complete asset are being compared.

In the case where a large number of alternatives are being considered with each other, it is important to keep in mind how things will behave when they are “packaged” together as compared to how they behave as separate items.

For instance, in the case of a single alloy vessel in a plant that is otherwise made of carbon steel, the turnarounds are still on a four-year cycle. That limits the benefit of a possible 10 year inspection cycle to a maximum of eight years or every other turnaround.

In the case of an all alloy plant, the inspection cycle for the entire facility might be expanded to 10 years. When you get to a ten-year inspection cycle, the entire asset would have only two inspections in the entire 30 year life. That would be a dramatic cost difference from the alternative involving outages every four years.

This subtlety can have a significant cost impact that becomes a synergistic effect of integrating reliability initiatives.

The same kind of thought-process can be applied to large fleets of similar assets like mobile equipment, construction equipment or transportation equipment. When the efforts needed to improve the performance of a single asset can be spread across a significant number of assets, the costs of engineering, development and testing can be significantly reduced by being shared by all instances.

There may even be cost advantages resulting from negotiating lower cost for the component being replaced when purchased in quantity.

LCC- Based Management versus the "Survival Mode" of Management

An unfortunate feature of life in the current business environment is the common practice of so many to seek immediate gratification. Rather than being willing to take the long view of investments, many people want to see a return on their investment within the immediate future.

Occasionally, this philosophy is driven by real economics. In those instances, immediate cash flow of the company and near-term prospects are so dire that the only objective being considered is immediate survival. The objective is to make financial choices that will allow the company to survive through today and manage tomorrow based on the situation that exists then.

Clearly, individuals operating in the day-to-day survival mode are not worried about the future costs of poor reliability. In their way of thinking, it is likely that all assets will operate through today. If they are no longer in business tomorrow, decisions made that avoid future cost were poor decisions.

While it is not a mistake for leaders to ask the people they lead to make survival mode choices if they really are in a survival mode, it is a mistake to do so if it is just a way to drive more current profits.

Driving a decision to purchase a one-year asset when the asset will be used for the next 20 or 30 years is a mistake the company will regret long into the future.

The practice of driving survival mode choices has become commonplace in business and industry. In many instances, it is the result of an overstatement or exaggeration of the current conditions. While it might make sense to eliminate discretionary maintenance or to trade near-term measurable risks for immediate savings, the purchase of long-term assets with features more appropriate to short-term economics is a mistake. Rather than purchasing an asset driven by one, two or three year payout periods, it would be better to delay the purchase until the future has become significantly clearer to avoid shortsighted decisions.

An important point to keep in mind is that senior managers and corporate executives seldom recognized shortsightedness of their decisions as they pertain to reliability unless explained to them by reliability engineers. It is the job of the reliability engineer to identify the risks and quantify the cost of those risks compared to the cost of immunity or prevention, then to publish their analysis to those who need to know.

LCC as a Way of Life

The concept of viewing all choices from the long-term perspective or from the perspective of lifecycle cost is one that changes the way you look at everything.

Rather than thinking about which alternative is cheapest you will ask which alternative has the greatest value and/or lowest Total Cost of Ownership. Rather than choosing the alternative that will deliver the greatest near-term profit, you will look for the alternative that balances near-term objectives with long-term needs.

Many companies spend their time dealing with past mistakes rather than being free of past mistakes so they can focus on current opportunities. Reliability and lifecycle cost analysis fit together to provide an environment free of past mistakes.

The failure risks you endeavor to identify when performing reliability analysis are all future cost that must be compared to current expenditures. In many cases, the costs of future consequences are overwhelming when compared to relatively minor costs of prevention.

Once lifecycle cost analysis is in place and being commonly applied, it is not uncommon for people to stop asking for the analysis to be done. It becomes obvious that the costs of prevention are almost always outweighed by the cost of untoward events when prevention is ignored. Even though the results of the analysis become second nature, it still makes sense to perform the analysis to keep people from becoming too conservative. Occasionally, the "run-to-failure choice is still the most economic.

Conclusion

This course focused on lifecycle cost analysis. Since much of reliability engineering introduces alternatives that cost somewhat more while reducing future expenses, lifecycle cost analysis is naturally linked to reliability analysis.

While in many cases the lifecycle cost analysis is used to compare a single element and just a few alternatives, it is useful for complete assets and many alternatives.

When safety or environmental impacts associated with one of the alternative are different from safety and environmental impacts associated with another alternative, it is important to include cost of those differences. If those differences cannot be monetized, they still need to be clearly stated in words when publishing the comparisons.

It is important to avoid focusing only on negative points that exaggerate the costs while not showing the positive benefits. Exaggerating a negative impact will affect your credibility. It is best to provide a balanced picture of results and to allow others to voice their point-of-view when poor performance naturally elicits an emotional response.

When the philosophy of using lifecycle cost analysis to make decisions becomes second nature, growing a history of making choices that produce optimum reliability, availability and total cost of ownership will soon provide an environment in which it will no longer be necessary to keep paying the price of poor choices made in the past.

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