Nuclear Plant Life Cycle Cost Analysis Considerations

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Abstract – *There is an increasing awareness within the nuclear power industry of the need to perform detailed life cycle cost analyses (LCCA) to quantify the risks associated with investing in new equipment that is needed to improve plant capacity factors. In undertaking LCCA, there are three primary factors that need to be addressed: What are the considerations that go into performing life cycle cost analyses; what tools are available for undertaking them; and, given constrained resources, how does a plant operator determine which improvement or set of improvements will provide the best return on investment? This paper provides some recommendations regarding these questions.*

I. INTRODUCTION

The nuclear industry has seen a substantial rise in average capacity factors over the past 15 years, with the average nuclear plant capacity factor rising to well over 90%. For those plants involved in continuous improvement, this trend has resulted a "good news, bad news" situation. While the plants have vastly improved stakeholder value, it has become increasingly difficult to not only justify investment in maintaining and improving plant availability but to choose between various options when faced with budget constraints. Given the size and nature of the improvement investments being proposed, the undertaking of detailed, quantitative life cycle cost analysis (LCCA) has become a necessity.

Typically when a LCCA is performed, the cost of the improvement, its expected benefit, and the net present value (NPV) of the proposed change are addressed. Items typically not addressed include the impact of equipment aging on performance, the variability of replacement power costs, and future sparing and maintenance costs. In this paper a comprehensive list of items that should be addressed during a LCCA is defined and the reasons for their inclusion are provided.

In order to undertake LCCA cost effectively, tools that can integrate all the disparate items of data information are required, such as the latest generation of LCCA assessment tools which are discussed in this paper. Improvements in computer technology that have dramatically increased operating speeds, memory, and storage have made the application of reliability, availability, and maintainability (RAM) simulation tools an excellent tool for addressing these needs. Taking into account issues such as equipment aging, overhaul effectiveness, reliability, maintainability, and cost variability, these tools provide time-based profiles of component and plant performance which in turn, provide a platform for addressing not only the initial cost of an investment but the spares, operating, and maintenance costs associated with that investment through the remainder of plant life.

Finally, once the means for performing LCCA on individual items is understood, a means for selecting a set of improvements given budgetary constraints is discussed. Typically, the authorization to make an investment is based on the merits of each alternative proposed. Unfortunately, this often results in double counting of benefits! A means for avoiding this double counting and for optimizing alternative improvement proposals is presented.

II. LCCA Defined

What is LCCA? LCCA underpins the life cycle management (LCM) process, providing a systematic means for addressing the costs and benefits associated with LCM decisions. The LCM work undertaken by EPRI, provides a definition of LCM [1]:

"Life cycle management is the process by which nuclear power plants integrate operations, maintenance, engineering, regulatory, environmental, and economic planning activities in a manner that:

1. Manages plant material condition (e.g. aging and obsolescence of systems, structures, and components -- SSCs),
2. Optimizes operating life (including the options of early retirement and license renewal), and

3. Maximizes plant value while maintaining plant safety."

The LCM process discussed in [1] consists of two parts – technical evaluation and economic evaluation. LCCA is process in which future costs for the acquisition, implementation, operation, and maintenance of new equipment or systems is addressed.

II. LCCA Considerations

In undertaking LCCA, there are number of aspects that must be addressed. These aspects may be broken down into the following categories:

- Cost and revenue influences
- Economic factors
- Determining the magnitude of change
- Data uncertainty

Each of these categories is addressed in the following subsections.

II.A. Cost and Revenue Influences

The objective of undertaking a LCCA is to determine whether a proposed action will result in benefit to the plant stakeholders. Figure 1, based on the Risk Informed Asset Management (RIAM) concept developed by South Texas Project Nuclear Operating Company (STPNOC) [2] provides a view of a comprehensive cost model that can be used to address the cost benefit of any proposed option. The goal is ensure that a proposed action will result in an increase in the plant's NPV.

With the premise that the model illustrated in Figure 1 is a closed loop system, the following observations are provided:

1. Any improvement offered that would reduce safety would probably be rejected. It assumed that a proposed reduction in safety would ether result in relicensing costs or regulatory action that would result in change that was not beneficial.
2. The areas most susceptible to volatility or uncertainty (and the primary cost drivers) are Market Prices for Electricity Sales, Unplanned Generation Losses, and Maintenance Costs.
3. The impact of unplanned generation losses and corrective maintenance (CM) costs are linked in that the frequency and duration of component and system failures affects the level of generation losses and the frequency and severity of component or system failures affecting CM material and labor costs.
4. The effect of efficiency and heat rate tends to remain relatively static over a given period. Changes, when they do occur, are relatively predictable because of the time and resources required to address engineering and regulatory issues.
5. The remaining revenue and cost areas can be forecast with some predictability and will typically have less of an influence on the benefit cost of a proposed improvement.

II.B. Economic Factors

Within the nuclear industry, the performance of a LCCA typically results in a calculation of the NPV of both benefit and cost of a proposed change.[1] A number of formulas for calculation of NPV exist. The following formula, contained in Appendix C of [1] is one that has been used frequently and proven to be acceptable:

$$\mathbf{NPV} = \sum_{j_{first}}^{j_{last}} C_j \left[\frac{1+k}{1+d}\right]^{(t_j - t_{NPV})}$$

Where:

NPV = net present value of LCM cost components through last period evaluated
j_{first}= first year for which costs are to be accumulated
j_{last}= last year for which costs are to be accumulated
C_j= year j cost in today's dollars
d= discount rate (cost of money)
k= inflation rate plus real escalation rate
tj= year in which cost is to occur
t_{NPV}= year for which NPV is to be computed

At some utilities, different values for the discount rate may be used for calculating the NPV of costs and benefits. Additionally, different rates may be used for calculating the NPV of hardware and of labor costs.

[1] It is recognized that other measures for accepting or rejecting a proposed change may be based on a positive benefit to investment ration or require a certain cash flow requirement. It can be argued that determination of these measures must still account for net value either on a periodic or cumulative basis.

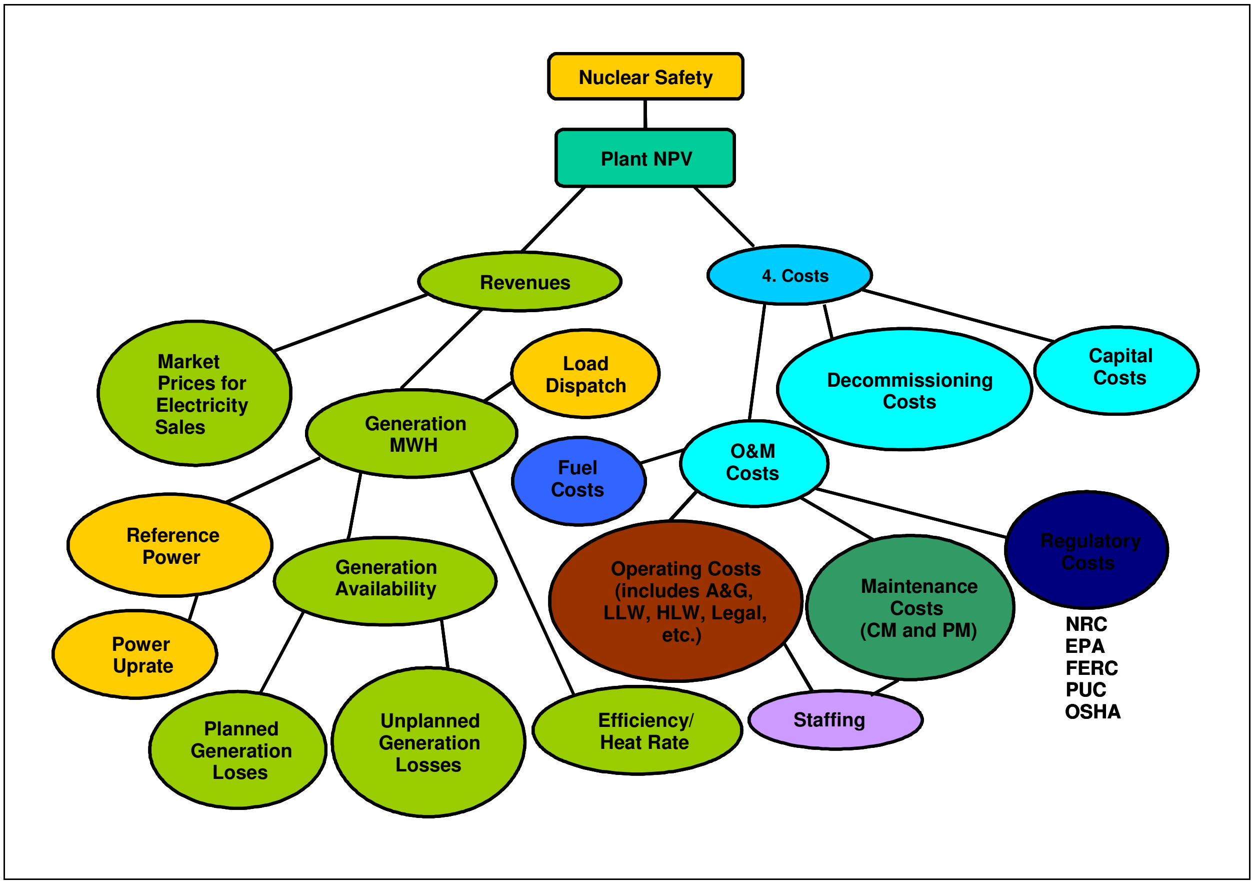

Figure 1. RIAM Value Map

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II.C. Determining the of Magnitude of Change

The performance of a LCCA relies on determining the expected change in the plant's capacity factor[2] that is attributable to a proposed improvement or set of improvements. Simplistically, the process is as follows:

1. A change is proposed and the cost of that change ascertained.
2. A model is used to determine the change in CF attributable to the proposed change
3. The change in CF is converted to a value using the following (or similar) equation:

Benefit($) =ΔCF x ($/MW-Hr) x Capacity (MW) x Period (Hr)

Changes in CF are either the result of a change in the equivalent availability[3] of a plant or its efficiency. Experience has shown that the majority of proposed plant improvement changes are focused on improving component and system availability rather than thermal efficiency. Because of this and the relative infrequency of efficiency improvements, this paper will focus on how changes in component and system availability affect changes in the capacity factor. It is assumed that there is a similar process for addressing changes in efficiency.

Reliability, or more appropriately, reliability availability, and maintainability (RAM) models are used to determine the magnitude of change in CF for a proposed change in component or system availability. Logic dependency models, typically represented by fault trees or reliability block diagrams (RBD), are coupled with appropriate failure frequency and repair data to calculate the capacity factor of the plant for a given set of conditions. To determine a change in CF, the failure rate and/or the repair time that characterize the proposed change are placed in the model and the CF recalculated.

The process described above appears relatively simple. However, its implementation can be complex and resource intensive. The RAM models developed to evaluate these changes not only require failure and repair

[2] Defined as the ratio of net electricity generated, for a given period of time, to the energy that could have been generated at continuous full-power operation during the same period of time.

[3] Equivalent availability accounts for generation losses due to derates as well as full outages.

data that is representative of the plant modeled they also need to address:

- Regulatory requirements (e.g., tech specs)
- The affects of component aging and overhaul effectiveness
- The operation of components and systems consisting of multiple trains (e.g., condensate pumps)
- The operation of standby systems and components
- The availability of maintenance and spare parts resources

II.D. Data Uncertainty

There is a significant degree of uncertainty associated with certain elements of LCCA. The primary uncertainties associated with LCCA are:

- The value of replacement power cost – influencing this are the affects of global and local market forces.
- Failure and repair data – typically, failure and repair data used in models reflect ***average*** values that represent the mean of an underlying distribution. Uncertainty can also apply to the amount of time a component is unavailable due to planned maintenance.
- Data distributions – the underlying distribution assumed for failure frequencies (and to a lesser extent, repair times) affect the behavior of RAM models. For example, if an exponential failure distribution is assumed, maintenance will have no affect on average availability. If however, a Weibull or Normal distribution is assumed, maintenance will have and affect.
- Logistics data – given a failure, the availability of spares (and the resources to effect the repair) can affect the time a component is inoperable. Should a spare not be available, the time required to order and receive the part can vary from a few hours to weeks, significantly increasing downtime.
- The values for inflation, escalation, and discount rates used for NPV calculations can vary significantly. During the 1980's and early 1990's, the inflation rate was consistently greater than the discount rate; recently the reverse has been true. While is difficult (if not impossible!) to foresee how these factors will change over time, their changing nature should be kept in mind when evaluating the NPV over a 10 to 20 year period

III. LCCA TOOLS

As seen from the previous section, the performance of a LCCA requires the integration of a number of factors. Indeed, for a typical plant, an LCCA will require:

- An availability model reflecting the operation and design of the plant
- Failure and repair data (and underlying distributions) for all systems and components reflected in the model
- Costs for:
  - Equipment procurement, installation, and test (or overhaul/refurbishment of current equipment)
  - Periodic maintenance (labor and material)
  - Spares
  - Replacement power
  - Fuel, operating, regulatory, and decommissioning
- Refueling and other periodic maintenance schedules
- NPV calculation variables
- Logistics data (spares order and ship time, labor mobilization time)

The performance of a comprehensive LCCA that integrates of all these factors could not be accomplished in a cost effective and timely manner if it were not for the existence of high-speed computers and relatively low cost, proven RAM assessment tools. The question then becomes, which tool might best meet the needs of a comprehensive LCCA? Is a fault tree or RBD approach desired? Ultimately the answer will be driven by the ability of the tool to integrate the above information, desired output, and the cost of developing/modifying models to support the LCCA.

III.A. PRA and RAM Analysis

In some minds, there is some confusion between probabilistic risk assessment (PRA) and RAM analyses. Since they rely on the same logical rules (e.g.,**OR**; **AND,** etc.) they are thought to be equivalent, but this is a misconception. The primary use of PRA is to address issues that affect the nuclear safety. Because of its nature, PRA is focused on determining the ***probability*** of an unlikely event occurring (i.e., core damage). The impact of the unlikely event on the CF is of secondary importance. PRAs are accomplished through the application of sophisticated software tools such as EPRI's CAFTA. Until recently, an overwhelming portion of reliability-oriented work has been done in support of probabilistic risk analysis (PRA).

In contrast to PRA, RAM assessment is focused on addressing the frequency of occurrence of more likely events and their impact on the ability of the plant to export power to the grid. Because of the historical focus on safety, relatively little RAM analysis has been done in the nuclear power sector. This is not true however in the gas turbine and steam fossil sectors. These plant types have been assessed using simulation-based RBD oriented applications that have recently become available.

III.B LCCA Output

The primary goal of a LCCA is to determine the cost benefit of a proposed plant improvement or change in an operations procedure. Management will not only want to know what is the cost benefit of a proposed solution is but will also wish to know the uncertainty surrounding that estimate. Table 1 is an example of results obtained by the author after performing a LCCA of a hypothetical case that involved recommending the best alternative proposed for a main generator improvement. These changes in NPV not only indicate the required net benefit and the uncertainty surrounding the mean value, they also reflect the variables discussed above.

PARAMETER (100K $)	ALTER-NATIVE B-A	ALTER-NATIVE C-A
Most Likely NPV Change	-1.26	6.23
Mean NPV Change	3.67	16.8
5%tile NPV Change	-4.22	-4.32
25%tile NPV Change	-0.75	5.91
50%tile NPV Change	2.23	12.9
75%tile NPV Change	6.29	24.5
95%tile NPV Change	16.3	51.5
Optimum Choice		**C**

Table 1. Improvement Alternative Benefit/Cost Results

These results are based on values reflected in graphs similar to that illustrated in Figure 2. That figure illustrates the distribution of potential NPV changes between Case A and Case B.

There are additional LCCA outputs that can support decisions based on LCCA. The output illustrated in Figure 3 provides a time based forecast of the costs and benefits involved in replacing Feedwater Heaters. Figure 4 is an example of a time-based forecast of for an example PWR unit with a two year refueling cycle. The benefit of this output is that provides a insight into the expected CF might be at any particular time in the future, allowing managers to plan for outages a times when demand may be less or, if there is a downward trend in forecast performance, determining the appropriate time to implement design changes.

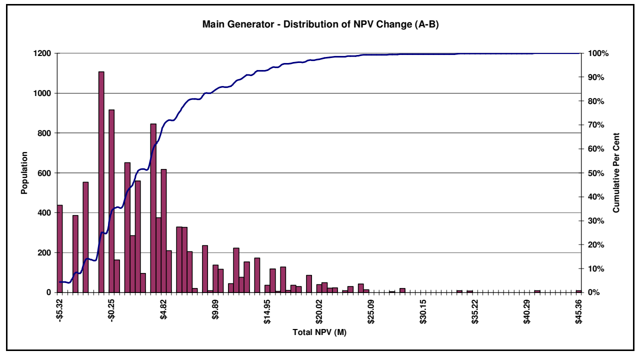

Figure 2. Distribution of NPV Changes between Case A and Case B

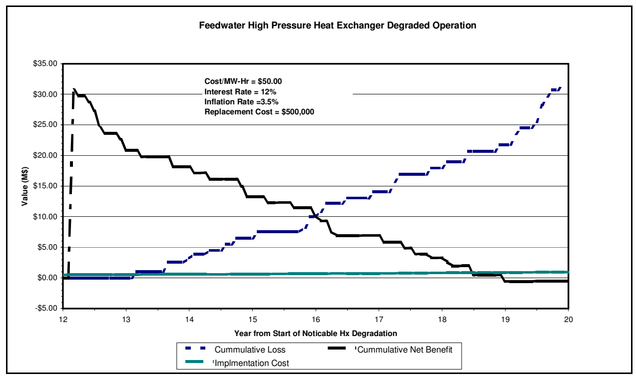

Figure 3. Feedwater Heater Operating Forecast

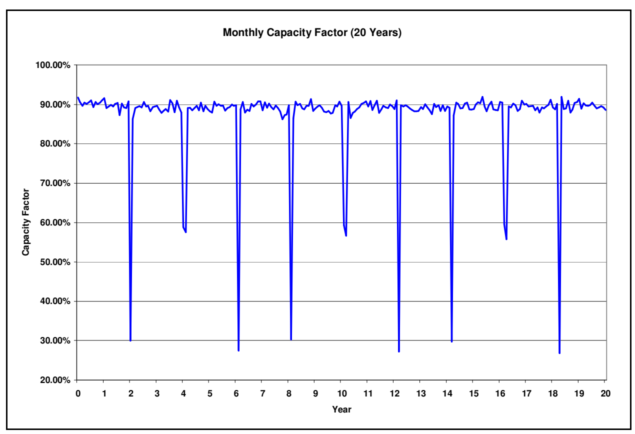

Figure 4. Time-based CF Forecast

III.C. LCCA Tool Selection

Given the range of inputs and uncertainties that must be addressed and the desired output, which tool is preferable for performing LCCA? The author believes that there are four criteria on which that decision must be based:

1. The ability to address component aging and maintenance effectiveness
2. Timeliness and ease of evaluation
3. The cost of the software used to support LCCAs.
4. The cost to develop the model and maintain it so that it reflects the "as built" condition of the plant.

To the author's knowledge, no single stand-alone application currently fulfills these criteria. To date, LCCAs have been performed using either:

1. A combination expected value RAM assessment tools (e.g., fault tree applications), electronic spreadsheet applications, and generalized commercial parameter simulation applications, or
2. A combination of a Monte Carlo-based RAM simulation tools and electronic spreadsheets.

Which of these tool sets is preferable? This question is best answered by an assessment of how well each tool set meets the listed criteria.

When the ability to address component aging and maintenance effectiveness are considered, the RAM simulation based tool is preferred. This preference is based on a number of technical reasons that are beyond the scope of this paper. (The preface to Reference [3] provides a detailed discussion of the fundamental differences between simulation and expected value modeling approaches). The simulation process relies on selecting failure frequencies and repair times from probability distribution functions. Since the simulation process tracks system and component age and is "aware" of time passed, the use of time sensitive distributions such as the Weibull accounts for component aging. It also allows for addressing maintenance effectiveness by resetting the age of the component to zero (or some lesser age) through the use of conditional logic within RAM simulation application. This is not the case with expected value systems because of an underlying assumption that failure rates are exponentially distributed and insensitive to time and repair.

The second criterion, timeliness and ease of evaluation, is driven by the need to support the decision process in a timely manner. Time frames for performing LCCAs are typically compressed, and, given the number of variables to be addressed, resources for performing them limited. Again, the RAM simulation-based approach is preferred. While an expected value application can determine the value of CF for a given set of conditions in the order of seconds, a significant number of these evaluations would need to be performed to account for each potential plant operating state, and, if so desired, determine the CF over time. This potentially large number of evaluations imposes a file management and post-processing regime that can slow the evaluation process. The time required to perform a LCCA evaluation using a RAM simulation application can vary from few minutes to a few hours depending on the complexity and size of the model, the number of life histories simulated, and the speed and capacity of the computer on which it is operated. Unlike the expected value applications, the simulation application uses and evaluates a single, unified model that accounts for all potential operating states and determines the value of CF over time. The file management burden is essentially eliminated and post-processing requirements reduced.

When the cost of the application software is considered, the expected value application tool would be preferred. Many of the expected value applications such as the EPRI sponsored CAFTA fault tree application are free to the nuclear utilities involved with EPRI's risk and reliability tools. For many other nuclear utilities, the cost of acquisition has already been amortized and is no longer an issue. Published costs for Monte Carlo-based simulation software vary from $10,000 to $75,000. These costs can be offset by the reduced costs involved in performing LCCAs and, when viewed in the context of the value they deliver and that they are used to support decisions that could involve millions of dollars, not unreasonable.

In the nuclear industry, when the cost to develop and maintain the model is considered, the use of non-simulation approach has a slight edge over the simulation-based approach. This is because most plants already have detailed models of the nuclear steam supply system that were developed for the performance of PRAs. In addition, the processes for managing quality assurance and configuration control are in place. However, very few plants have developed models for balance of plant systems – the systems that are most likely to be the cause of generation losses. In a recent development, efforts have been undertaken that will allow the automatic incorporation of PRA fault tree elements into RAM simulation models and thereby reducing the costs of model development.

IV. IMPROVEMENT OPTION SELECTION

Typically, a LCCA is performed to address the advisability of implementing a specific improvement option or selecting the best one from a range of options. The process is focused on evaluating a given component or system, independent of improvements proposed for other components or systems. The selection of the range of improvements optimized to provide the greatest return to the plant, as a whole, is not a straightforward process of selecting alternatives based solely on a single criterion such as expected NPV. A number of different elements must be addressed:

- Is there sufficient budget available to implement a set of projects in a given year?
- Even if sufficient budget is available is there sufficient outage time available to implement a proposed change?
- Does a proposed change in component availability have a linear affect on unit availability? If one is dealing with redundant components or systems (e.g., four condensate pumps operating n parallel with three at any one time required for 100% plant output), the assumption of linearity is incorrect. In the redundant case, especially with installed spare capacity, no discernable improvement in unit availability will occur unless the availability of more than one pump is improved. Moreover, the improvement in the availability of each additional pump will not result in equal improvements in unit availability.
- Given competition for resources between different units, how is a proposed improvement selected that benefits the company as a whole?

One possible means of addressing these complexities was developed by EPRI in the late 1980's and is still valid [4]. The process, summarized below, was applied to fossil units at two different utilities [5]. At one utility it was used to optimize the implementation of approximately 30 different proposed alternatives at three units. At the other, it was used to optimize 180 proposed alternatives at 12 different units. In both cases, the process resulted in a reduction in the investment required and an increase in the forecasted return.

The improvement life cycle cost optimization process employs a four-step iterative approach as illustrated in Figure 5.

The first step in the process is to collect the information and data related to the improvements under evaluation. The second step is to apply an economic screening criteria and method to determine which improvement options are potentially cost beneficial. The third step considers various constraints such as funding limitations, outage schedules, and manpower limitations to further evaluate the candidate improvements. The final step of the approach is to evaluate surviving candidate improvements through a dynamic program algorithm to arrive at a

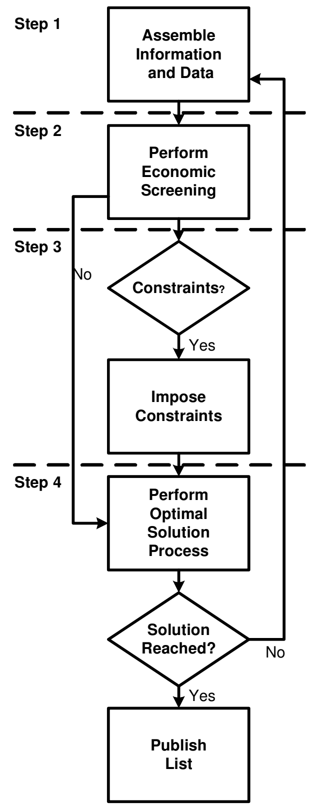

Figure 5. Cost Optimization Process

sequence of improvements that provide the greatest net benefit within established constraints. As will be shown, LCCA applications like those discussed above would be used in steps 2 and 4 of the process.

IV.A. LCC Optimization Step 1 – Data Collection

In order to implement the life cycle cost optimization process it is necessary to establish a relationship between the cost of implementing an improvement and the expected benefit of that improvement. That relationship is established by determining the cost of the improvement, estimating the expected increase in component availability resulting from that improvement, calculating the effect of the component availability change on overall unit equivalent availability or capacity factor and converting the change in unit equivalent availability into a benefit based on an increase in net generation revenue. To accomplish that, the following information is required:

- A listing of the reliability, availability, maintainability (RAM), and efficiency improvement options under consideration
- The cost required to implement each improvement option

- The time and resources required to implement each change
- For RAM improvements, the actual or estimated change in event frequency and/or downtime resulting from each improvement option
- For efficiency improvements, the expected percent increase in net revenue from either decreasing the fuel cost or in increasing net generation capability.
- An LCC simulation or expected value model and associated baseline data for the plant (or plants) to be evaluated
- The cost relationships between unit availability and costs such as replacement power, fuel, and operations and maintenance expenditures
- Identification of funding, schedule, or other resource constraints
- Economic factors such as escalation, discount, and interest rates

A LCC model is used to assess changes in unit availability that may occur due to changes in component RAM characteristics so that the relationship between availability and production costs can be studied quickly and accurately. The need for information relating to constraints is required because the cost optimization methodology must be responsive to the possibility of limited capital, outage time, or the labor and engineering resources available for implementing improvements. This is especially true for improvement projects that must compete for funding.

IV.B. LCC Optimization Step 2 – Economic Screening Analysis

An economic screening analysis is used to identify those candidate improvement options that have the potential for producing a positive net benefit. This initial economic screening assumes that the proposed improvements are independent. Before beginning this analysis, a LCCA would be performed for the plant (or plants) to evaluate the effect that changes in component availability have on unit production. The output of the evaluation would be a criticality ranking (C_i). This ranking indicates, for each component or event, the increase in unit productivity to be expected if that component were to achieve "perfect" availability, i.e., its availability becomes 1. The forecasted change in component availability for a given proposed improvement (ΔA_c) is then multiplied by he component's criticality ranking (C_i x ΔA_c) to calculate the approximate change in unit availability that can be expected from implementing that change. This initial screening relies on the assumption that the relationship between component and unit availability is linear. As Figure 6 illustrates, this relationship can be non-linear. However, the relationship can be linearly approximated for small changes in component availability. For each proposed RAM improvement, the expected increase in unit production is then used to estimate the increase in annual megawatt hours that may be expected from a specific component improvement. To calculate the change in expected megawatt hours (ΔMW-Hr), the following equation is used:

$$\Delta \text{MW-Hr} = \Delta A_u \text{ x (Unit Net Capacity) x (Scheduled Operating Hours)}$$

The increase in power production can then be converted to an expected revenue increase and compared to the cost of making the component improvement.

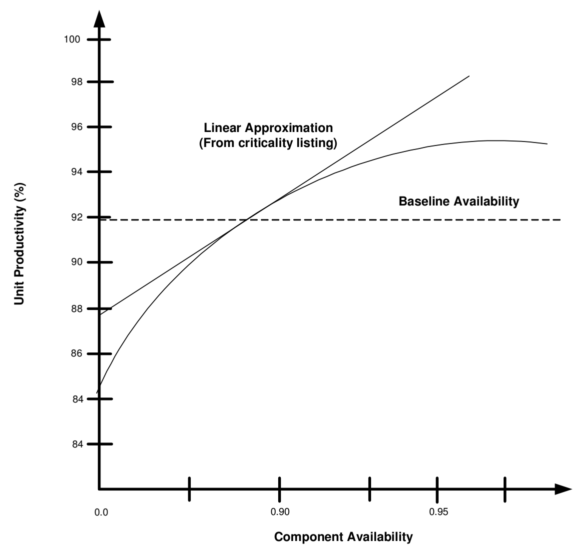

Figure 6. Component/Unit Availability Relationship

Improvements proposed for increasing efficiency would be economically screened as follows:

- If the proposed change resulted an increase in net capacity, the benefit would be calculated using the following equation:

  $$\Delta \text{MW-Hr} = A_u \text{ x } \Delta\text{(Unit Net Capacity) x (Scheduled Operating Hours)}$$

  As before, the increase in power production can then be converted to an expected revenue increase compared to the cost of making the component improvement.
- If the proposed change resulted in lowering fuel costs, i.e., less fuel is required to generate the

same amount of power the following equation would be used to calculate the expected benefit:

Benefit = MW-Hr's x Δ(Cost/MW-HR)
Where MW-Hr's = A_u x (Unit Capacity) x (Scheduled Operating Hours)

Should there be other cost factors affected by changes in unit productivity, these too can be estimated in a similar manner. Those component improvements that would provide a cost savings greater than the investment cost then become potential economically viable improvement candidates because, as we will see later, they may be dropped from consideration for other reasons. If so desired, the present worth of the costs and benefits can be used in the economic screening process to account for the time value of money over the life of the change.

The output of the economic screening process is a list of potential economically viable improvement projects. These projects, with their costs and benefits, are then analyzed considering additional constraints (e.g., minimum cost-benefit ratio, must do for regulatory reasons, negative impact on safety, etc.) that may be desired.

IV.C. LCC Optimization Step 3 – Optimization with Constraint

The third step of the analysis considers any stated constraints on the improvement process such as funding limitations or manpower resources. If there are no constraints, or the constraints are not exceeded, the optimization process can proceed to the optimal solution process. If the limitations of any constraints are not satisfied, an integer program (IP) algorithm is applied to the economically screened candidate improvement options prior to last step. The objective of the IP algorithm step is to choose the combination of improvements that provide the optimum benefit while satisfying the limitations of each constraint. The IP step assumes that the benefit resulting from each specific improvement will not affect the benefit of other improvements and that the total benefit is the sum of each individual benefit.

The result of using the IP is a list of candidate component improvements that maximize the net benefits and meet the imposed constraints. If the assumption of independence and linearity reflected the actual relationship between component and unit availability, the IP would provide the final optimum set of improvements. However, as seen in Figure 6, the relationship between component availability and unit availability is often non-linear and experience with LCC models has shown that component improvement effects are not independent.

IV.A.4. Step 4 – Optimal Solution Process

The final step in the optimization process is to apply a dynamic programming (DP) algorithm to the set of candidate improvement options. The objective of the DP algorithm is to optimize the solution set taking into account any non-linearities that exists between component and unit availability and any interdependency that can exist between components. This is done by making a sequence of selections, which if the process were prematurely terminated, the changes selected to that point would still be optimal.

As each component improvement is selected and the baseline design or operation of the unit is changed (via the LCCA model), then the ratio of changes in unit availability to changes in component availability of the unmodified components will either increase, decrease, or remain the same. Because of these changes, it is possible that some component improvements that were previously not cost beneficial will become beneficial. Conversely, it is also possible that some improvements will no longer be beneficial. The unpredictable effect of changes on component criticalities (C_i) is investigated using the DP algorithm. Note that this DP algorithm is dependent on the same constraints imposed by the IP algorithm.

The DP algorithm is a process that methodically addresses the expected benefit of implementing alternative sets of improvement candidates to ascertain the set that will provide the greatest net benefit. As each improvement candidate is implemented and the baseline design or operation of the unit is changed (via the LCCA model), the economic screening and imposition of constraints processes are again done on an iterative basis. The economic screening is accomplished with the new baseline design; the imposition of constraints is accomplished with a reduction in the constraint equal to the cost of the candidate improvement(s) implemented.

The result of these optimal analyses is a chronologically ordered list of recommended improvements that should provide maximum return on an improvement investment considering all constraints.

This process has a great deal of relevance to utilities in that it provides a repeatable, verifiable process for determining for selecting proposed LCM projects when faced with limit budgets and other constraints. Because of the nature of the process, it results in a rank ordering of projects that will provide the greatest return to the unit or owner.

V. CONCLUSIONS

The objective of this discussion has been to highlight some of the critical issues that need be addressed by nuclear utilities in undertaking LCCA. The foregoing has only skimmed the surface of issues that need be addressed when a LCCA is undertaken. It has described, at a high level, the requirements and some of the pitfalls that must be addressed when undertaking plant LCCA as well as providing a suggestion for optimizing the selection of improvement projects. The foregoing was not intended to be a comprehensive discussion of the various aspect of LCCA – discussions and approaches related to life cycle management program requirements, RAM simulation, fault tree analysis, power plant economics, etc. have been discussed and documented in detail by plant personnel, EPRI, and by various consultants.

NOMENCLATURE

A – Availability
CF – Capacity Factor
DP – Dynamic Program
EPRI – Electric Power Research Institute
IP – Integer Program
LCCA – Life Cycle Cost Analysis
LCM – Life Cycle Management
MW-Hr – Megawatt-Hours
NPV – Net Present Value
RAM – Reliability, availability, and maintainability
RBD – Reliability Block Diagram
RIAM – Risk Informed Asset Management

REFERENCES

1. M. Arey, et. al., *Demonstration of Life Cycle Management Planning for Systems, Structures, and Components -- with Pilot Applications at Oconee and Prairie Island Nuclear Stations – EPRI Report 1000806*, Electric Power Research Institute, Palo Alto (2001).

2. C. R. Grantom P.E., "Risk-Informed Asset Management (RIAM) for Nuclear Power Stations - Concept Overview and Applications Examples," *Presentation*, *ANS Utility Working Conference,* Amelia Island, FL (2002).

3. A. Dubi, *Monte Carlo Applications in System Engineering*, John Wiley & Sons Ltd., Chichester, United Kingdom (2000).

4. S. Hall and R. Unkle, *Demonstration of An Availability Optimization Methodology – EPRI Report GS-2462-1*, Electric Power Research Institute, Palo Alto (1989).

5. .S. Hall and J Weiss, "Life Extension – A Strategy for Cost Optimization," *Proceedings, Life Assessment and Extension*, Vol. III, p.190, Nederlands Instituut voor Lastechniek, The Hague, The Netherlands, 1988.