Using Financial/Decision Analysis Risk Optimization to Prioritize Maintenance Expenditures, Justify Maintenance Spending and Maximise the NPV Savings of The Maintenance Function

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ABSTRACT

- Converting maintenance and engineering expenditures into cash flows enables maintenance to compete with other parts of the business
- Through decision/financial analysis, selection and timing of repair and refurbishment projects can produce positive NPVs for the station
- Examining the critical inputs to the prioritisation of the predictive maintenance plan:
  - Probability of failure with time
  - Loss of production costs
  - Repair vs replacement cost of key components
  - Budgetary cost constraints
- Quantifying the savings and increase in NPV where maintenance optimisation has been used
- Highlighting the long term and short term implications of key component maintenance to get the most valuable prioritisation of maintenance projects

Keywords: predictive maintenance; risk based; decision analysis; net present value; aging; maintenance planning; inspection planning; remaining life analysis; probability of failure

INTRODUCTION

Increasingly across the base infrastructure industries of industrialized countries, engineers are finding it difficult to obtain the necessary resources to maintain expensive equipment. This is especially critical in gas turbines and combined cycle gas turbine power facilities with short life cycle hot section components and older boiler tube components. Predictive maintenance was developed to focus on equipment requiring maintenance resources. However, engineers have been and are ill equipped to convincingly "tell their story" to the decision-makers. This paper suggests a process to aid this communication and guide corporate resources into predictive maintenance expenditures to maximize value.

THE NEED TO CONVERT MAINTENANCE AND ENGINEERING TO A FINANCIAL BASIS

Competing For Resources

Engineers are finding themselves competing against other segments of the corporation for investment resources to support maintenance, especially in the electric power production and petrochemical industry. These industries are finding an extreme limitation put on maintenance resources. Engineers are having a difficult time being heard because they do not normally speak in financial terms and do not usually have the necessary tools to compete in this arena.

Competition for corporate resources occurs on the turf of corporate finance, using fully-accepted quantitative methods. Increasingly, the control of financial resources in these industries is in the hands of financial decision-makers. The methods used in this arena to judge one investment versus another have been financial analysis and decision analysis.

Limited Maintenance Resources

The limitation on maintenance resources comes from rising maintenance cost and a lowering of product unit prices. This situation may not be true for other parts of the corporation, which are feeling the effect of lower prices, but not the severe upward pressure analogous to rising maintenance costs.

Until this point in history, a sound engineering analysis was considered adequate to convince management that maintenance expenditures were necessary. However, corporate resources have tightened, and engineering analysis alone has lost the appeal necessary to obtain maintenance resources. In short, engineering for engineering's sake is loosing its strength.

Any time that resources become more limited, more quantitative methods are used to aid in tough decisions using systematic input processes. Because choices are not as clear, there is a need to extract all possible information from inputs, and to process this information in a very quantitative manner in an attempt to promote more objectivity and ease of review.

Equipment Aging

The upward pressure on maintenance cost comes from equipment that is in the aging part of its life cycle. Most major components in the hot sections of gas turbines and combined cycle gas turbine power facilities are in or rapidly approaching the aging part of their life because of their short life cycle in hot section components and older boiler tube components. These are short life cycles as compared to the typical electric utility power plant or petrochemical facility components.

The typical life cycle curve, shown in Figure 1, shows the classic shape of the Weibull life cycle curve.[1,2] To the left is the decreasing failure rate of the curve, usually called infant mortality. It is dominated by failures from initial defects, either in manufacture or design. The center section is a period of constant failure rate that I call the honeymoon period. This is the period when minimum prudent maintenance causes the failure rate to remain constant. This period is the sum of infant mortality and the aging part of the life cycle. The right section is the aging period and has an exponentially increasing failure rate because of the dominance of aging failure mechanisms. This life cycle curve is classic and can be used to describe the life of not only engineering components, but almost anything in nature that has a birth, life span, and death. What is experienced in equipment is very normal and predictable.

Industry has been surprised by the large increase in maintenance cost for conventional components of industrial facilities installed 30 to 50 years ago. During the constant failure rate period, it was generally felt that if prudent maintenance were performed, the rate of failures would not increase. This is the period of the life cycle when many present day managers gained their experience.

The original plan by engineers was to replace equipment at the end of its life cycle, in anticipation of aging. However, competition has prevented the necessary resources being available. This is because no single country now dominates world markets. As a consequence, corporations are faced with the need to keep aging equipment running with limited resources.

Competitive Pricing

The advent of improved worldwide transportation, reduced single country market domination and multi-national corporate ownership have resulted in downward pressure on unit product pricing to meet competition. This has caused a limitation on financial resources available to companies for maintenance and operation.

Maintenance Resources Caught Between Aging Equipment and Competitive Pricing

The limitation on maintenance resources due to lower prices, and the increased need for maintenance resources because of aging, has placed maintenance decision making in a dilemma. In the past, when there were more resources, there was more margin to be conservative and to include maintenance actions that may not have been entirely necessary. With current and future limited resources, this degree of conservatism can no longer be tolerated. More fully quantitative techniques are now needed to better discriminate between maintenance actions.

USING DECISION/FINANCIAL ANALYSIS

Decision analysis, supported with financial analysis and optimization techniques, is already being used for large investment decisions when large segments of resources are involved. It can be found as part of a course, or as a whole course, in almost every MBA program in the U.S., and in many foreign countries. This method for decision making was developed almost 30 years ago[3] to account for conditions of uncertainty. It is very well suited for maintenance decision making because of the uncertainty of trying to maintain equipment during the aging part of its life cycle.

Decision analysis fits the situation for maintenance, when limited resources make decisions not as obvious. This requires fully quantitative methods that can stand the test of challenge and review. The methods that have survived for a long time are those of decision analysis and financial analysis. This is because they are classic and well grounded in the principals of probability theory and of maximizing long term return to the stockholder. Their appeal has been their ability to fully quantify and process input information through a decision model.

As I began to work with the financial decision making side of companies, I found that using decision and financial analysis techniques is an accepted way of doing business. Many companies were already accustomed to looking at financial decisions on a fully quantitative basis, and accounting for uncertainty in the decision in a fully quantitative manner, using classical methods. In addition, I found that the presentations expected by senior management were based on these methods. In essence, I found an already accepted method. It seems reasonable, therefore, to use the same techniques for maintenance decision making since maintenance is competing for the same resources.

BASIC DECISION/FINANCIAL MODEL FOR PREDICTIVE MAINTENANCE

Decision Criteria

In decision analysis, the first decision to be made is the criterion to be optimized. Based on the textbooks used most frequently in MBA corporate finance courses, this criterion would be Net Present Value (NPV).[4] This criterion insures that there will be a maximum return for the invested corporate dollar when decisions are being looked at over multiple years. In addition, some of the more recent terms used to emphasize stockholder value of a corporate investment are maximized when NPV is maximized. This makes NPV the most robust of the financial criteria to be used for optimization.

There is a danger, practiced by some engineers, in sometimes using reliability as a criterion for decision making. Reliability is an engineering term, not a financial term. It is not well understood in the battle for corporate resources. Secondly, reliability and NPV analysis can produce the same results when the equipment of concern is in demand a high percentage of the time. However, the difficult maintenance decisions are those for not highly utilized equipment. In this case, NPV will guide the decision toward highest value, rather than highest reliability, since highest reliability is not always needed.

In the case of maintenance, the Net of Net Present Value is created by looking at the choice between two maintenance decisions.[5,6] The first possible decision is doing nothing different. That is, run the equipment as it is, performing normal routine maintenance. This we call the base case. We consider the consequence of shutdown or derating as a result of keeping the aging equipment operating. The intent of the maintenance action is to avoid this consequence. We call this the benefit of the maintenance action, since we are taking credit for preventing the consequence of shutdown or derating. The second possible decision is to take a mitigating maintenance action to avoid the potential consequences of failed equipment and shutdown. This we call the alternative case. It is the cost of taking maintenance action. Here, we look at the cost of the maintenance action, plus the consequence of a shutdown or derating that might still occur due to the maintenance action not being perfect.

The diagrammatic representation of this is shown in Figure 2 by a decision analysis influence diagram. This diagram is constructed by placing the decision criterion to be optimized on the right. The diagram and its relationships are constructed as we ask the question, “What do we need to know to determine the NPV in this case?” We need to know the benefit and cost side as shown above and below the horizontal line in Figure 2. The consequence of failure without the action is the benefit, and the cost is the cost of the maintenance action plus the consequence of failure with the action. Ultimately, on the far left we have the decision of whether or not to take the action represented in a square. Note that this diagram establishes a relationship between the decision, the specific terms in the maintenance action and its consequences, and the decision criterion of NPV. What you see in this diagram is the cash flow streams created by the relationships in this decision problem.

The Present Value part of Net Present Value considers the effect of taxes and the time value of money. Because maintenance decisions on aging equipment have to do with timing, this is an important consideration in any maintenance decision analysis. In taxed corporations, the tax effects on maintenance expenditures, as well as losses declared from shutdowns or deratings are significant. Engineers usually are not concerned with these but, in the financial arena, they need to be accounted for. The same is true for time value of money. This accounts for inflation and the expected return to be passed to the shareholder. The discount rate is usually used, so that the expected return for the invested maintenance dollar has to meet or exceed a minimum desired return to the shareholder over time.

The Link Between Engineering and Finance

Perhaps one of the most important steps in the fully quantitative process is the conversion of engineering analysis results to financial consequences. The barrier to understanding the engineering position on an important maintenance project proposal is that the engineer usually speaks in engineering units, such as time to failure or probability of failure. He talks of the probability of occurrence, not consequence of occurrence. "Consequence of occurrence" is a term that business-oriented managers understand. Engineers need to convert engineering units into financial units.

The term that the decision-maker is most concerned with is not whether a component will fail, but what this failure will mean to the health of the company. A more accepted term in engineering and other technical communities with which to describe this is risk.[6] Risk is defended as the product of probability of occurrence and consequence of occurrence. In the financial community, this same formulation is called the expected value of the consequence.[5] Because of this similarity in definitions, we now have a common link between the engineering world and the financial world. This relationship, defined by risk or expected value of consequence of failure, will be a key in the formulation of the decision model for fully quantitative maintenance decision making.

This key is further represented in the development of the maintenance action decision influence diagram, shown in Figure 3. Note the addition of the probability of failure, consequential failure cost, and the conversion of the consequential failure cost node into the expected consequential failure cost nodes. The "with" and "without" maintenance action cash flow streams create the net value of the decision criterion. The year to perform the maintenance action is added to this figure given that it has been decided to perform the action. The arrows that may seem strange in this figure are the ones pointing from year of performance of the action to the probability of failure without the action, and the one pointing from the probability of failure without the action to the expected consequential cost with action. The reason for these two arrows is to establish the relationship for the expected consequence of failure, if the maintenance action is delayed. During the delay to the year in which maintenance action is performed, the expected consequence of failure will be the same as if the project action had not been taken. Note that after the year to perform the maintenance action, the probability of failure with action is used to determine the expected consequential cost of failure with the action.

Probability of Failure with Time

The use of "probability of failure" with time is an all-inclusive expression of the engineering condition of the equipment. For many years, worst case analyses were performed. A probability of failure is set to an absolute certainty, the value of one, with full consequences at that same time for purposes of financial analyses. By intent, this approach is very conservative. Worst-case scenario inputs in this type of analysis are meant to account for the uncertainty in the inputs. However, engineering input is limited to the worst side of the distribution rather than using the whole distribution. In addition, engineering, by using single numbers for lives, was, by implication, leading decision makers to believe that the equipment condition was more precisely known than it, in fact, was. The use of full distributions to describe inputs is an all-inclusive description of the inputs and their uncertainty, rather than just a restrictive worst value. The advent of probabilistic fracture mechanics started an awareness that a complete expression of the engineering state of the equipment could best be expressed with a probability of failure versus time curve. It is clear from the financial discussions above that an expression of the engineering condition of the equipment in this form directly integrates into already established classical probabilistic, decision, and financial analysis methods.

Constraints

The further linking of this maintenance decision process to the real world is shown in Figure 4. Note that the maintenance budget limit constraints is added. In many electrical utilities there is a corporate policy to use a forced rate limit as a performance index. This influence diagram shows how this constraint is incorporated.

OPTIMIZING THE DECISION MODEL

The objective in decision making is to optimize the decision criterion. In this maintenance decision situation, we are trying to determine a maintenance action year to maximize NPV, while not exceeding either of the constraints of maintenance budget limit or forced outage rate limit. The goal is to optimize NPV by maintenance action timing.[5,6]

Operations research methods can perform this function on the decision model described. In fact, the decision model has been constructed in a spreadsheet model, and an operations research type optimizer has been written as a spreadsheet macro.[5,6,7]

Financial Inputs

The financial assumptions used in this type of analysis are usually well established in the financial organization of a corporation. For the engineer, it becomes a matter of seeking them out. These financial assumptions need to be included because they have significant effect on the timing of the maintenance project. In addition, in a fully quantitative analysis, they are significant.

The first set of financial assumptions affect the time value of money. First is the projected inflation rate, to account for the eroding value of the dollar with time. Second is the corporate discount rate used to insure that any investment is expected to have a return that is at least equal to the planned return for the stock and bond holders.

An assumption seldom thought of is the composite income tax and the property tax rates.

Of these two, the composite income tax rate is the most significant and has a large effect on the value of a maintenance decision. The effect is that financial loss consequence can be viewed as a business loss, and a significant portion can be written off. The impact of the maintenance cost itself can be greatly reduced for the same reason, if the maintenance cost is classified in an expense category. If the maintenance cost is capitalized, it still can be written off but at a much lower rate, over time, through the tax effect of depreciation.

Engineering Inputs

On large maintenance decisions, a lack of credibility is created in the mind of the financial decision-maker when excessively large financial consequence estimates, and the worst case probability of failure, are used. However, if a prudent, fully quantitative engineering probabilistic analysis or assessment is performed, and the financial consequences of a failure are appropriately estimated, there is more credibility to the risk or expected value of the consequence provided to the decision-maker. As a result, it is appropriate in aging large equipment maintenance decisions that the engineer use all possible technologies to assess the condition of the equipment from the standpoint of failure.

The area of probabilistic fracture mechanics best describes these techniques. These techniques establish a damage propagation mechanism mathematical model with a failure criterion. This model is then integrated over the range of input distributions with a "Monte Carlo" program or fast probability integration techniques. This integration produces a probability of failure verses time curve.[5,6]

There are less rigorous methods that are fully quantitative for obtaining the probability of failure versus time. These methods are good for obtaining preliminary engineering inputs for the maintenance decision analysis. This allows a first level look at the possible allocation of maintenance resources. The first of these methods is the trending of failure history data on a plant component of concern, or on similar components at other plants. A method used for this is standard linear regression analysis using the Weibull distribution function. The reason for using this function is that it was derived to express the reliability of equipment with time. It has been used extensively for this purpose. A second method is a structured interview for future failure projection with plant personnel most familiar with the equipment. This method is called a probabilistic assessment interview, or expert elicitation. It was developed by cognitive psychologists in the decision analysis community over the last 15 years, and has been extensively used with senior corporate executives on large corporate decision analyses.[5,6,7]

The Bayesian update analysis is a classical method of combining failure history projections with plant personnel structured interviews. The Bayesian method, developed several hundred years ago,[8] focuses on the combination of current probabilistic information of an event with newly found information for the same event, resulting in updated information.[9] It is objective and can be used to combine failure history projection data and plant personnel interview projections, using a weighted averaging technique based on the normalized product of the two projections for each year. Using a technique of this type provides better projection of the future failure probability because of the use of both data sources. In addition, using these preliminary techniques allows the decision to be assessed inexpensively as a first iteration in order to determine the need for a higher cost, fully quantitative engineering analysis.

THE EXAMPLE OF COMBUSTION TURBINE BLADE REFURBISHMENT

The Situation

The utility does not want to perform a blade refurbishment or replacement too soon. This is because of the relatively high capital cost for a row of blades. The utility wants to wait until a turbine wreck and forced outage is a real possibility, but not a real threat. Replacing too soon will result in a high maintenance expense when there is no real threat. Replacing too late will result in a decrease in expense because of the value of money, but if put off too long can result in a very costly turbine wreck and forced outage. The need for an economically timely refurbishment or replacement of blades for a combustion turbine operator is necessary to be able to minimize this unnecessary maintenance expenditure.

The Model

The measurement of the present state of the blade coating and temperatures, as well as the engineering modeling accomplished by a remaining life model, provides the probability of failure projected into the future operation of the machine. The decision analysis model, depicted in Figure 5, would serve a bridge between the engineering analysis and the decision world based on economics. The model illustrates the use of the measurement data from inspection, the analysis by life prediction codes, and the bridging to the financially significant consequences of turbine wreck and forced outage costs. The model also includes the competing expenditures of refurbishment or replacement cost held within the operator's budget constraint.

The spreadsheet that is constructed for this model would be exercised not only for each year of action, but also in the other dimension of type of action to be taken. The goal of finding the action alternative and year to maximize the NPV and remain within the constraints is still the same.

THE EXAMPLE OF TURBINE OVERHAUL TIMING DECISION

The second example decision is the delay of a turbine overhaul beyond the OEM recommendation. The question, based on financial reasoning – When is it estimated that the overhaul needs to take place without creating a negative value for the company?

The influence diagram for this decision is shown in Figure 6. This diagram is constructed in the same way as described above. In this case, however, we are dealing with the timing of a maintenance decision. The upper half of the diagram represents the benefit we are claiming because we are trying to time the cost of the overhaul to avoid the consequence of a shutdown and its associated damage.

The overhaul is estimated to be $350,000. If there were a failure in the hot section the down time, cost are expected to be $1,000,000 for repairs and 500 hours of lost revenue due to the shutdown at $2,000 per hour, weighted by a utilization factor of 60%. The probability of failure of the hot section is represented by the cumulative probability of failure versus time curve in Figure 7. The Net Present Value versus Overhaul Year curve is shown Figure 8 with a peak in 1998 of $79,495. This is the optimum positive value producing time to perform the overhaul. The curve is fairly flat for another year, indicating that the overhaul could be delayed until 1999 with essentially the same positive value result. From 1999, however, the curve drastically decreases with a negative net value being created after 2001. This curve provides a sense of the sensitivity of the value of the decision with time. It particularly highlights when the overhaul is being delayed too long to add value to the corporation.

Both of these examples have been included to demonstrate how the information gathered in this study can be used in construction of financially-based maintenance decisions for presentation to senior management in a language and form that they are accustom to.

EXAMPLE FOR BOILER TUBE COMPONENT REPLACEMENT

An example of decision analysis supposes a boiler tube component of the superheater or reheater type. The concern is if, and when, to spend $1,000,000 for replacement of the entire component. The failure in this example is the burst of any tube segment, resulting in the shutdown of the entire power unit. It is assumed that the unit will be down for 24 hours for repair of each tube burst. The unit has a 150MW maximum dependable capacity, with a projected capacity factor increasing from 25% to 55%, with the replacement power cost for this unit increasing from 20$/MWH to 55$/MWH over the next twenty years.

The probability of failure versus time is based on a remaining life analysis, as shown as the base case in Figure 9. This is the expected probability of tube burst versus time curve, given no replacement and given that the unit continues to operate, causing the next less efficient unit in the dispatch to be operated upon tube burst. The alternative case curve assumes that the boiler tube component is replaced. Here, the probability of failure curve is lowered due to the replacement action. NPV is generated by decreasing the probability of failure by replacement of the boiler tube component.

Note from Figure 10 that the highest NPV is created by replacement of the component in 1998. Note, also, that the highest NPV is positive, which means that the boiler tube component should be replaced, creating the highest value, if performed in 1998.

CONCEPT OF A MULTIPLE COMPONENT DECISION

In reality, *numerous* maintenance projects are competing for the maintenance budget simultaneously. Maintenance optimization is defined here as the performance of a decision analysis process that maximizes NPV for many maintenance projects simultaneously. In a utility, all projects can be annually constrained by the maintenance budget limit, which means that maintenance optimization needs to be conducted with all individual maintenance decision models linked.[5,6,7]

Maintenance optimization has several benefits. The more maintenance projects, and the larger the portion of the maintenance budget that is modeled, the larger the expected value benefit that can be realized. In addition, decision analysis more closely represents the real maintenance budget decisions that are being made, and is performed using a systematic, fully quantitative and reviewable process.

For maintenance optimization, the decision model previously described in Figure 4 is expanded. For each additional project, the associated two probabilities of failure and year of maintenance action nodes will be added to the influence diagram and also to a spreadsheet. The multiple maintenance projects optimization then provides a prioritized list of decision alternatives and years of maintenance action that creates the maximum NPV for the group, while staying within the constraints. This is accomplished in a spreadsheet by inserting different combinations of years of action for each maintenance project seeking that combination for the group that maximizes total NPV without exceeding the constraints. This is accomplished through an operations research algorithm approach.

An example of the benefit of this approach was demonstrated with a PC-based spreadsheet model, applied to 140 forced outage critical fossil plant tube components across a power system.[5] The estimated resulting NPV of the optimization was in the tens of millions of dollars.

CONCLUSIONS

A Fully quantitative maintenance decision analysis model can:

1) Be optimized for the timing of the maintenance actions, maximizing the value of the maintenance dollar to the corporation;

2) Create a link between engineering and the financial decision maker as a result of the common definition for risk and expected value of consequence of failure; and

3) Allow engineering to compete for corporate resources during times of tight budgets.

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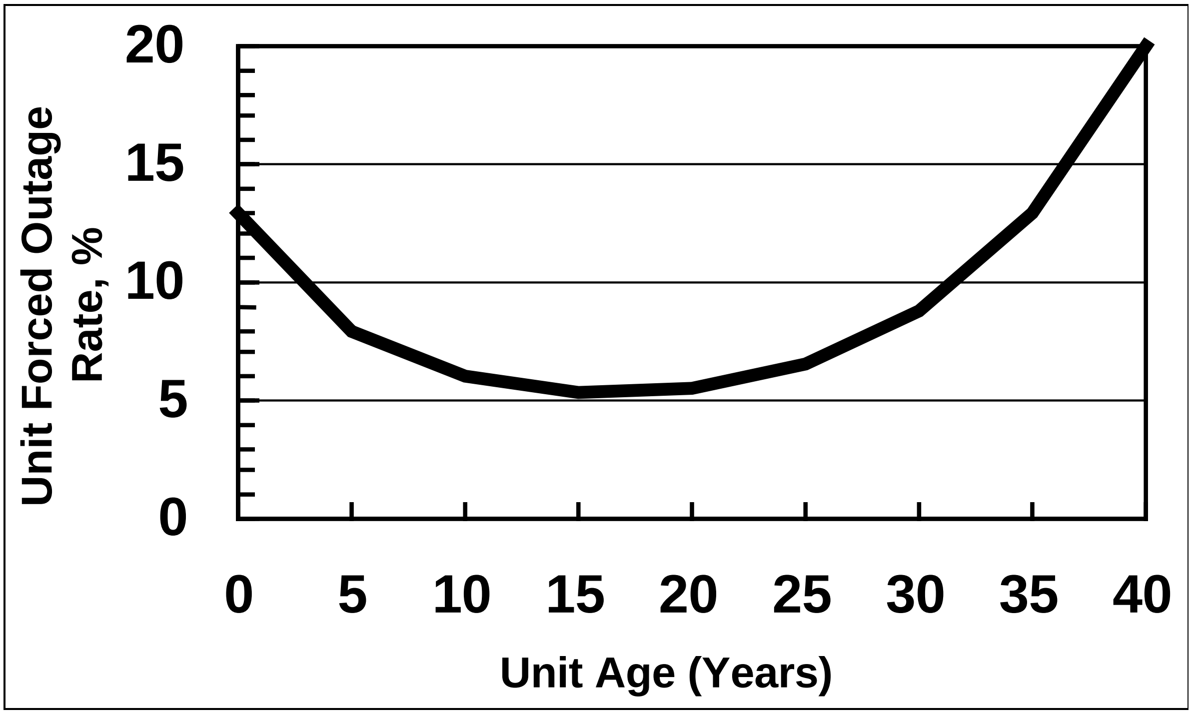

Fig. 1 NERC-GADS Data for Forced Outage Rate for Coat Fired Units from 50MW to 200MW.

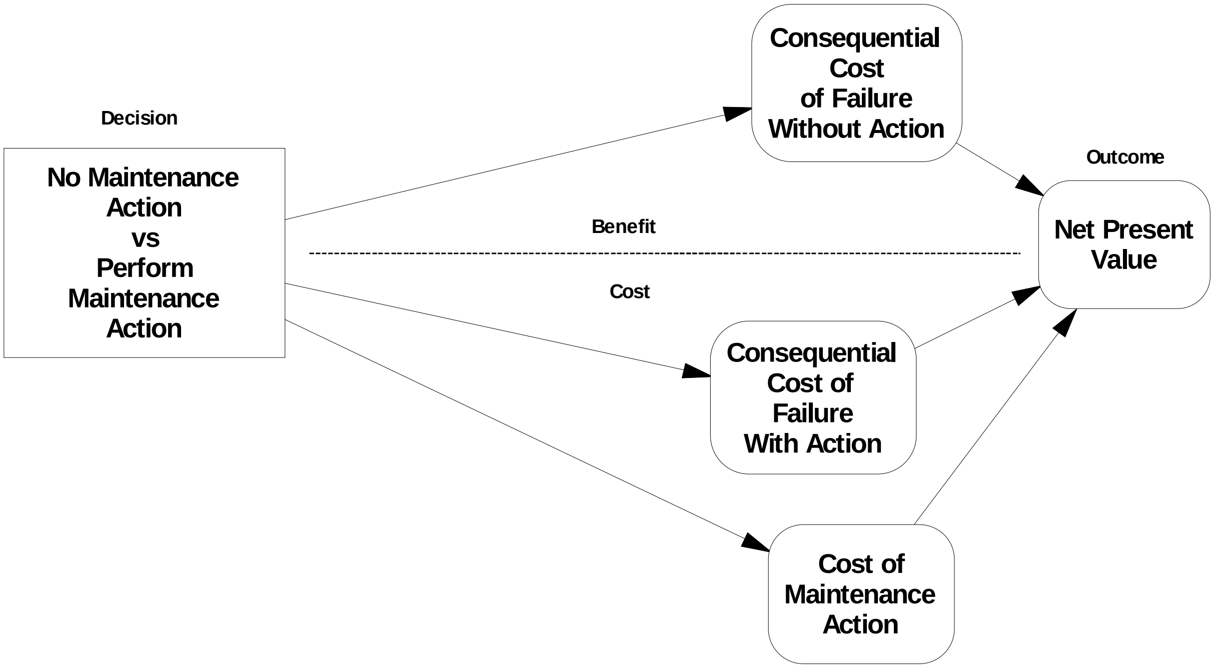

Fig. 2 Emphasizing the Links Between Net Present Value and the Maintenance Action Decision.

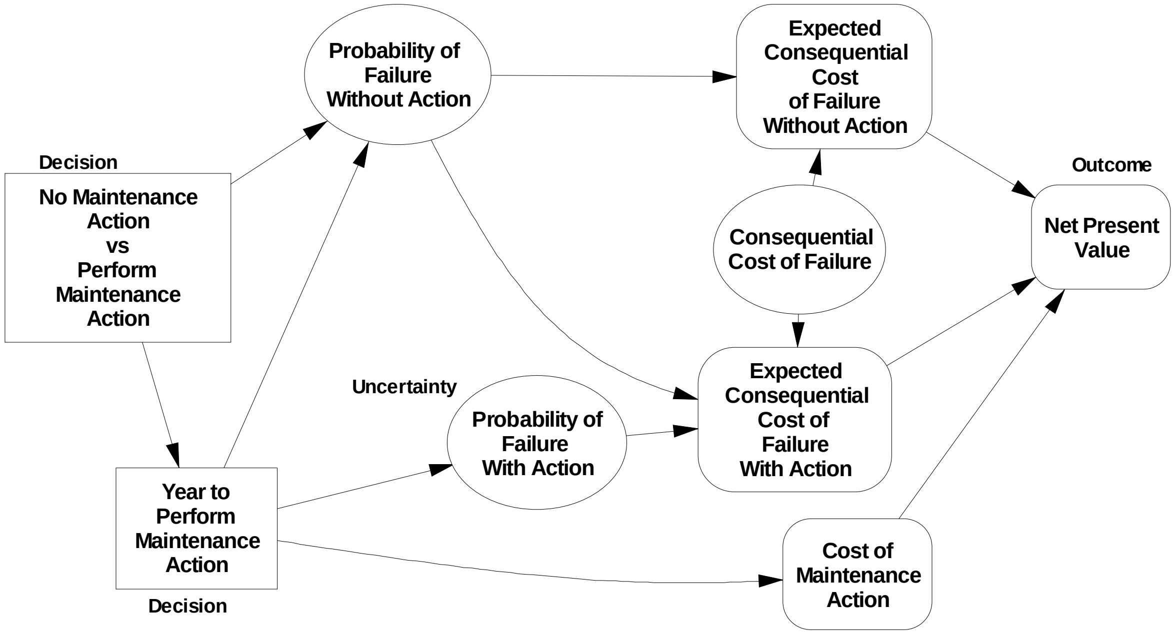

Fig. 3 Influence Diagram Emphasizing the Replacement of Consequential Cost with Expected Consequential Cost or Risk.

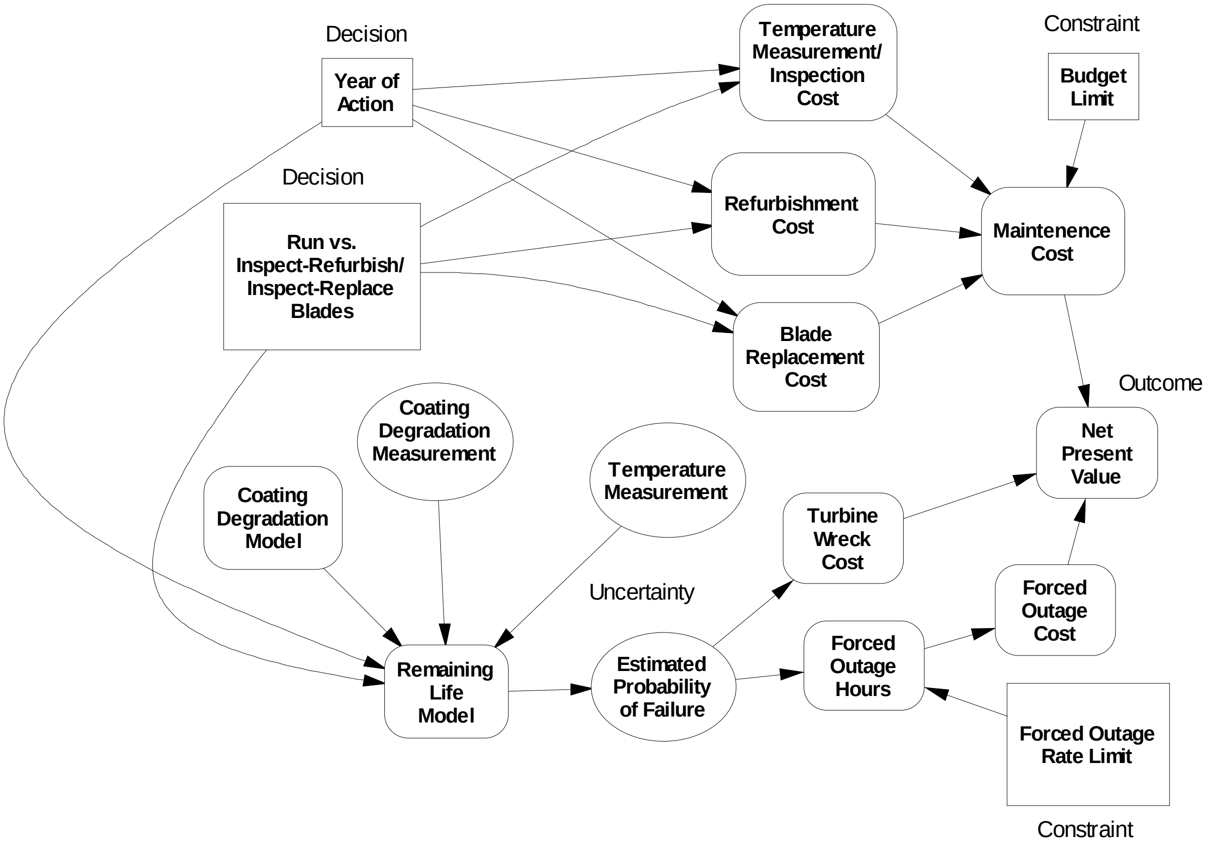

Fig. 4 Influence Diagram Emphasizing the Timing of, and the Constraints on, the Maintenance Decision Process.

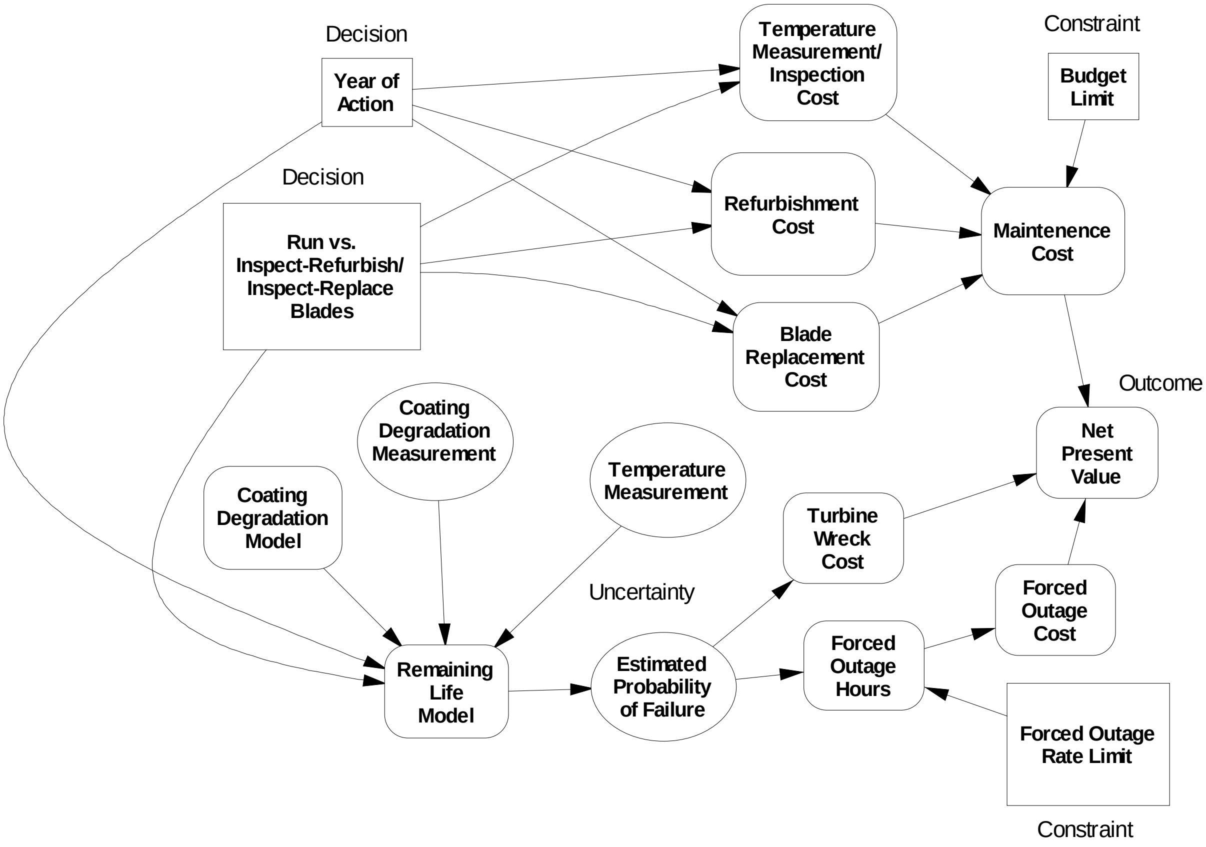

Fig. 5 Influence Diagram Emphasizing the Timing or Refurbishment or Repair of Gas Turbine Blades.

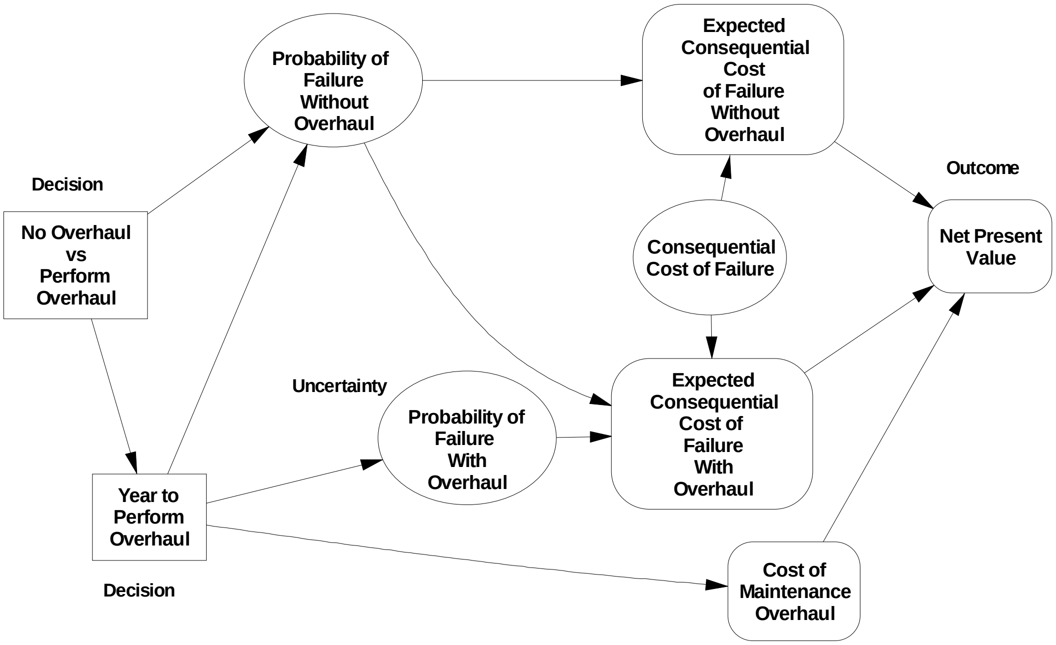

Fig. 6 Influence Diagram Emphasizing the Timing of an Overhaul.

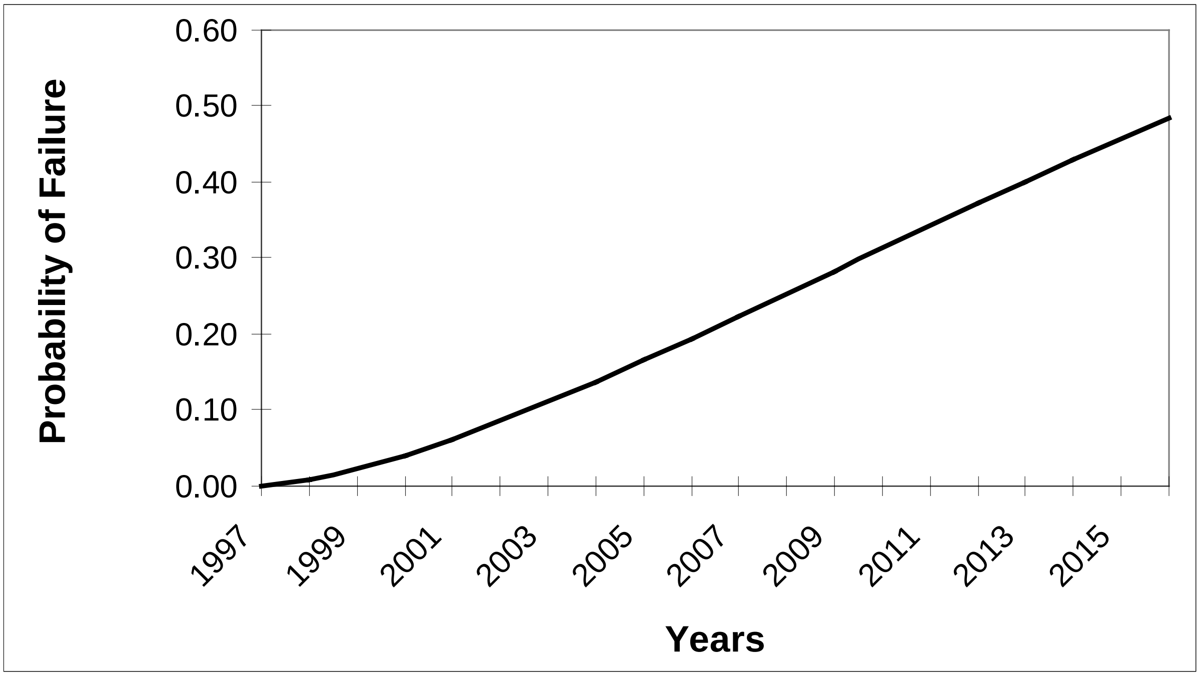

Figure 7 Gas Turbine Hot Section Component Probability of Failure Vs. Time

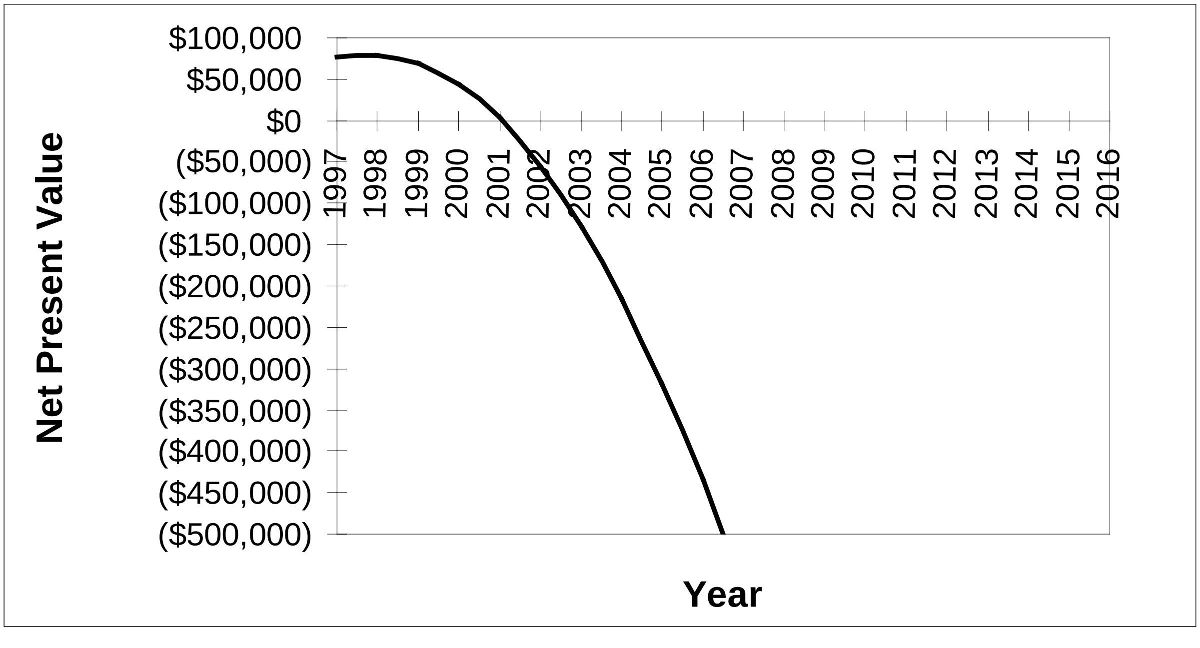

Figure 8 Net Present Value Vs. Maintenance Action Year for Gas Turbine Hot Section Overhaul Example.

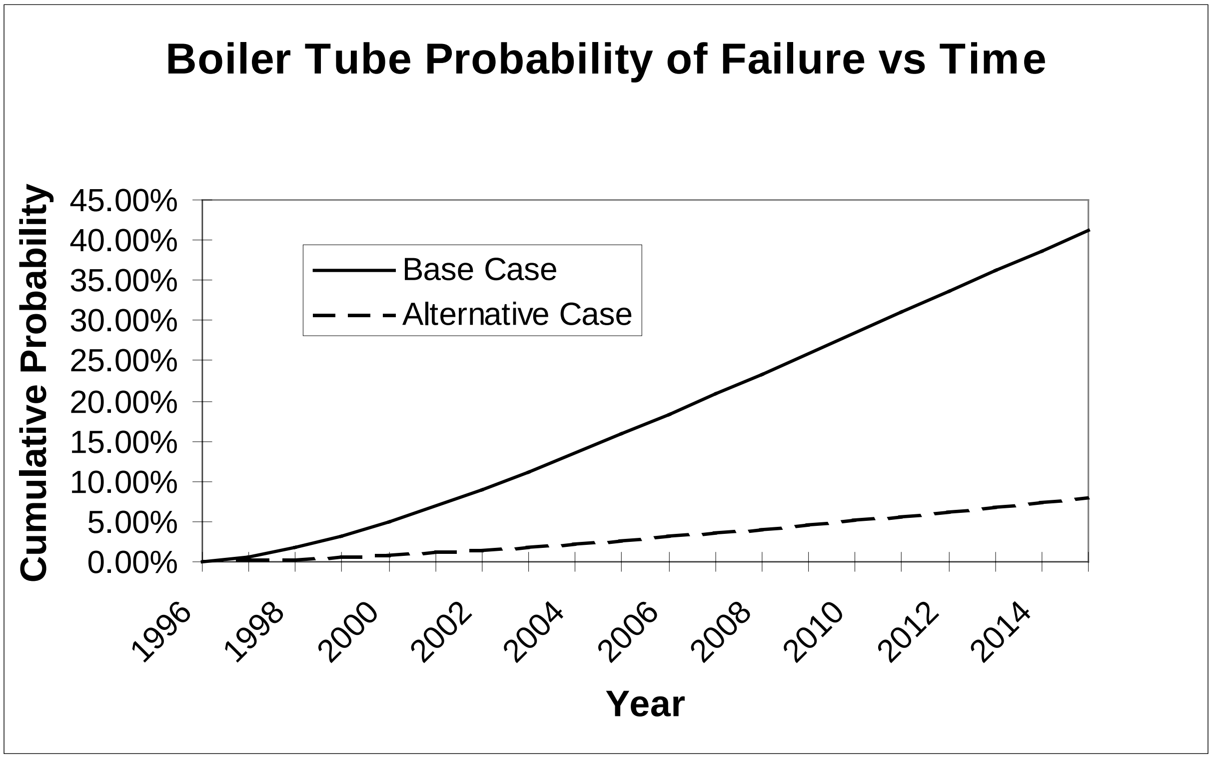

Fig. 9 Boiler Tube Probability of Failure Vs. Time.

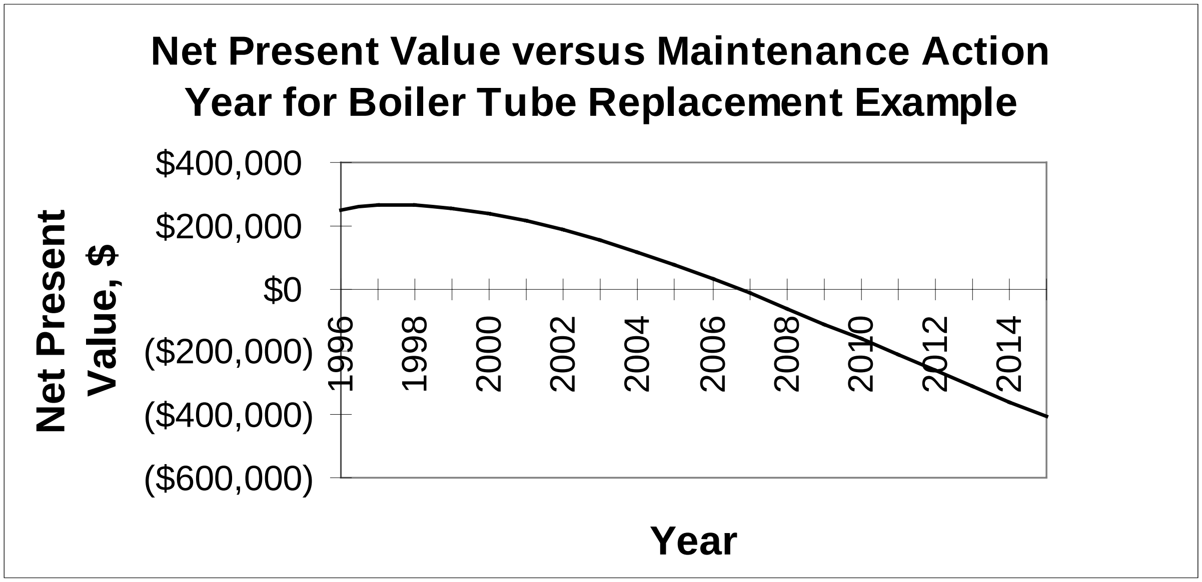

Fig. 10 Net Present Value Vs. Maintenance Action Year for Boiler Tube Replacement Example.