Warranty and Maintenance Decision Making for Gas Turbines

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Abstract

In this paper we describe ongoing research in the areas of maintenance and warranty decision-making for gas turbines used in power plants. We first frame the problem within a larger context of equipment monitoring, diagnostics and maintenance. We then focus on describing and modeling economic issues related to warranty maintenance service from the perspectives of both the consumer (power plant owner) and producer (General Electric). Finally, we develop a dynamic programming approach to optimize specific compressor maintenance activities for a fixed warranty period.

Introduction

The gas turbines which are used in power generating plants are highly complex, multi-component, multi-sensor units which represent significant capital investment. Because power plant operators rely upon these units for revenue generation, it is highly desirable for the gas turbine to function above a minimum performance level for the duration of its operation life. AI techniques have been effective in the areas of on-line sensor validation, sensor fusion, diagnostics and maintenance (Goebel, et al, 1997, 1999). The turbine manufacturer can go one step further by building on this monitoring and diagnostics experience and capabilities in offering an integrated product warranty package. In exchange for paying the producer a fixed warranty price plus the price of the turbine itself, the power plant, or consumer, is provided with all preventive and other necessary parts and service required to maintain the unit above some specified performance level for the length of the warranty. Purchases are guaranteed for a fixed period of time.

Both the producer and consumer are modeled as profit maximizing entities. We present the producer with a dynamic programming tool to assist in determining warranty price, warranty length, and maintenance strategies for profit maximization. Modeling the system with an influence diagram, this research enables the decision maker to account for tradeoffs related to the many choices available due to the uncertain, multi-component, multi-sensor gas turbine environment. For example, regular maintenance of a part may increase overall efficiency and prevent component failure but may also incur costly system downtime. A simple example is discussed, preliminary simulation results are evaluated, and application of the research to a specific compressor maintenance activity is mentioned.

This research considers the scenario where the gas turbine manufacturer, or producer, offers a service warranty to the power plant operator, or consumer. By offering the warranty, the producer agrees to provide all labor and parts necessary to maintain the turbine for a fixed period of time, the life of the warranty. Each party is assumed to be a profit maximizing entity; the power plant prefers a warranty of lower cost and longer duration, whereas the turbine producer wants to extract higher profit through minimal maintenance activities and a warranty of higher cost and shorter duration (Chun 1992; Dhepunar and Jack 1992; Nakagawa 1990).

Compressor water wash is an important job for the maintenance of the engines (General Electric 1996; Hamilla 1996). In general, the compressor performance is the main determinate of the working efficiency of the machine. The compressor degradation comes from various factors, such as dirt, erosion, blade damage. Therefore, the maintenance jobs generally include on-line and off-line wash, inspection, scouring, and blade replacement. If these maintenance jobs are done periodically by the warranty provider, an immediate question that arises is how often each should occur during the warranty. The answer determines how we can run the machine at minimum expected maintenance cost while incurring minimum profit loss, which is caused by the efficiency degradation.

This paper addresses the key issues of maintenance planning and warranty definition. In order to allow the manufacturer to maintain the product at no extra cost to the consumer during the warranty period, we develop a methodology to derive an optimal maintenance decision strategy of whether the producer should replace or repair some components of the engine at present, given the sensor values (temperature, pressure, etc.). This strategy is crucial to help the producer decide whether to repair or replace any subset of the engine's parts, whether more information is needed, or whether no action is appropriate.

Warranty and maintenance decision making in this paper revolves around four key issues which form the basic outline for this paper.

- How many turbine engines should the customer purchase, if any?
- How much should the manufacturer charge for a gas turbine engine/warranty?
- How long should the warranty period be?
- What types of maintenance and sensing activities should the manufacturer pursue?

Consumer Profit Maximization

Consumer profit maximization takes up the first question, namely how many turbine engines should the consumer purchase, if any. We will assume that the engine and warranty are bundled, that is, they must be purchased together or not at all. A rational consumer will choose an optimal number of gas turbine engines to purchase from the engine manufacturer in order to maximize consumer profit. We first assume the following variable representation:

j= customer
w = warranty length
p1 = engine price
p2 = warranty price
nj = the quantity of engines customer j buys
μ = the mean life of the turbine engine
Rj(nj,w)= the revenue customer j makes during warranty, given w and nj.

Therefore, the consumer wishes to maximize the difference between revenues, costs, and losses by choosing an optimal number of turbines to purchase. Then for all j, consumer j would

$$\underset{n_j}{\text{Maximize}}\ R_j(n_j,w) - (p_1 + p_2) * n_j^* - (w/\mu) * \text{shutdown loss.}$$

Producer Profit Maximization

Producer profit maximization addresses the issues of how much the manufacturer should charge for a gas turbine engine/warranty and how long the warranty period should be. In order to maximize its profit, the producer must determine optimal prices for the gas turbine and warranty and also an optimal warranty period length. We now assume additional variables for the following:

m = maintenance cost given the maintenance strategy
x_t = average efficiency level during period t
F_t (x_t, s, t_s) = the expected minimum maintenance cost from the end of period t to end of warranty

The producer will now maximize profit by solving the following problem:

$$\underset{p_1,p_2,w}{\text{Maximize}}\ (p_1 + p_2 - m) * \Sigma n_j^*$$

Subject To $m=F_0\ (x_t, s, t_s)$.

Dynamic Programming Approach to Optimal Maintenance Policy

This paper focuses mainly on the final issue, namely, how the manufacturer determines the types and number of maintenance and sensing activities it should pursue. We use the concept of dynamic programming (Dreyfus and Law 1997) to investigate this very issue. In order to deal with this problem, we assume that the compressor working performance is the main determinant of engine efficiency levels, the other parts of the machine have long life cycle (compared to predetermined warranty length, w) and keep running stable. Four primary decision options are available at the end of each period: on-line wash, off-line wash, major inspection, and do nothing, say decision alternatives 1,2,3, and 7. If decision 3 is taken, a secondary action should be taken among three additional options: major scouring, blade replacement, and do nothing, say decision alternatives 4, 5, and 6. These options are illustrated in Figure 1.

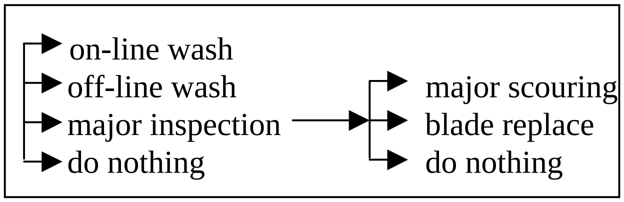

Figure 1: Decision Alternatives

Based on the above information, this problem can be formulated by stochastic dynamic programming. In order to simplify the problem, the efficiency is expressed by a discrete state variable rather than a continuous one. Similarly, the engine condition is also modeled to be discrete. The transition probabilities between efficiency levels and between engine states are machine characteristics which can be determined through a range of AI and statistical techniques, including on-line statistical analysis, expert subjective probabilities, on-line machine learning and knowledge extraction from fault and repair logs.

Notation

We explain notation for our model in the following:

w = the number of warranty periods;
t = current time period;
t_s = the time period the last major inspection was made;
x_t = the average efficiency level during period t;
$c(d_i)$ = the cost of decision option I;
$loss(x_t)$ = the profit loss at efficiency level x_t during one period;
s = perceived engine state at last inspection;
s’ = current engine state;
v = total maintenance cost;
$P(s'| s, t-t_s)$ = the transition probability to engine state s' at time t from s at time t_s;
$P(x_{t+1}| x_t, s', d)$ = the transition probability efficiency levels;
x_{t+1} at time t+1 from x_t at time t, given engine state s’ at time t and decision d (d_1~d_7);
$F_t(x_t, s, t_s)$ = the expected minimum maintenance cost from the end of time period t to the end of warranty, given x_t, s, and t_s ($t_s < t$).

The influence diagram describing this model (Barlow and Pereira 1993) is shown in Figure 2. The decision affects both s’ (current engine state and the total maintenance cost. We have assumed that x_t , the engine state, which describes functionality peripheral to the compressor and thus unaffected by actions to the compressor, is unaffected by the user’s decision, d.

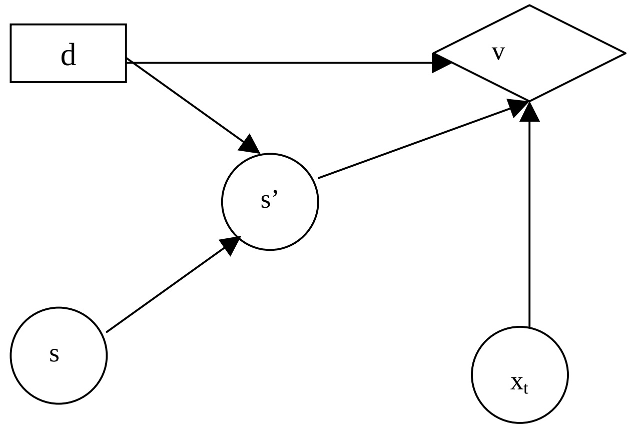

Figure 2: Influence Diagram

Assumptions

Important assumptions for this formulations include:

- The compressor working performance mainly determines the engine efficiency levels, with the other parts of the machine assumed to have long life cycles (compared to warranty length).
- Working efficiency is expressed by a discrete variable; engine state is also discrete and describes the parts of the machine not related to the compressor.
- Maintenance activities are done at the end of each period.
- The gas turbine runs at one efficiency level during one period; this is the machine average efficiency during this period.
- The probability to the next engine state depends on the current state, which is known.
- The transition probability between efficiency levels from the current period to next period depends on the maintenance job on the compressor and the machine condition.
- The customer purchases the brand new machine which operates at efficiency level 1.

Formulation

At the end of each period t, given the current efficiency level x_t, the time period t_s when the last major inspection was made, and the perceived machine state s by the last inspection, the minimum expected cost from current time to the end of warranty corresponds to the optimal decision among different decision alternatives. Each decision alternative gives the expected cost which equals to the decision cost and the minimum expected maintenance cost from next period, t+1, to the end of warranty. Compute the minimum expected cost backwards period by period, and the minimum expected cost for the whole warranty is obtain. Moreover, it's assumed that the customer buy the brand new machine (engine state 1) at best efficiency level (level 1). The ideas addressed above can be implemented by the formulation shown as following:

Decision alternative 1, d_1, is the choice of an on-line water wash.

$$c_1 = c(d_1) + \sum_{s'} \sum_{x^{t+1}} P\left\{x_{t+1} \middle| x_t, s', d_1)\right\}$$
$$\bullet P\left\{s' \middle| s, t - t_s\right\} \bullet \left[loss(x_{t+1}) + F_{t+1}(x_{t+1}, s, t_s)\right]$$

Decision alternative 2, d_2, is the choice of an off-line water wash.

$$c_2 = c(d_2) + \sum_{s'} \sum_{x^{t+1}} P\left\{x_{t+1} \middle| x_t, s', d_2)\right\} \bullet$$
$$P\left\{s' \middle| s, t - t_s\right\} \bullet \left[loss(x_{t+1}) + F_{t+1}(x_{t+1}, s, t_s)\right]$$

Decision alternative 3, d_3, begins with the choice of a major inspection. Upon inspection results, an additional selection is also made between a major blade scouring (d_4), a blade replacement (d_5), and no additional action (d_6).

$$c_3 = c(d_3) + \sum_{s'} P\left\{s' \middle| s, t - t_s\right\} \bullet$$
$$\min_{d = d_4, d_5, d_6} \left\langle c(d) + \sum_{x^{t+1}} \begin{matrix} P\left\{x_{t+1} \middle| x_t, s', d)\right\} \bullet \\ \left[loss(x_{t+1}) + F_{t+1}(x_{t+1}, s', t_s)\right] \end{matrix} \right\rangle$$

Decision alternative 7, d_7, is the do nothing action.

$$c_7 = \sum_{s'} \sum_{x_{t+1}} \begin{bmatrix} P\left\{x_{t+1} \middle| x_t, s', d_7)\right\} \bullet P\left\{s' \middle| s, t - t_s\right\} \bullet \\ \left[loss(x_{t+1}) + F_{t+1}(x_{t+1}, s, t_s)\right] \end{bmatrix}$$

The dynamic program iteratively solves the following equation at the end of each period, from the last period backwards.

$$F_t\ (x_t, s, t_s) = \min\ [\ c1, c2, c3, c7\ ]$$

This is subject to the following boundary condition:

$$F_{w+1}\ (\text{-}, \text{-}, \text{-}) = 0\ .$$

The last step is for the dynamic program to solve

$$F_0 = loss(1) + \sum_{s'} P(s'|\ 1, 1)^* F_1(1, s', 0)$$

which gives the producer's minimum expected maintenance cost for the entire warranty period.

One thing which should be mentioned here is the boundary condition, F_{w+1} (-, -, -) = 0. It is clear that no cost is incurred by the warranty provider when the warranty ends. So we can use the formulation to compute the minimum expected cost function F_t backwards from the boundary condition.

Simulation and Results

The dynamic programming approach to optimal maintenance planning described in this paper was simulated using Matlab ™. This simulation assumed several inputs. Variables manually input by the user included: length of warranty period, costs for the various decisions (on-line, off-line, major inspection, major scouring, blade replacement, and do nothing), and input losses incurred at the four possible efficiency levels. Furthermore, the simulation retrieved from another source the transition probabilities for state and efficiency changes.

Following user input of the above variables, the simulation yields the resultant expected minimum maintenance cost. Once the minimum expected overall maintenance cost is acquired, the simulation program can be used to find the best action for any single period, given the current efficiency and period and last-recorded state along with the period in which the state was assessed. This additional action would yield the minimum remaining expected minimum cost through end of warranty, thus allowing the user to optimally choose actions for any period, given current conditions.

Preliminary testing of the simulation looks promising. Given high major scouring costs, decision 4 was not an optimal decision in most situations. In addition, a high profit loss resulting from efficiency level 4 led to immediate action, via blade scouring or replacement.

The efficiency and state transition probabilities played an important role in determining the optimal decisions taken. Although we do not have any empirical data on which to base reasonable assumptions for the state transition probabilities (divided into three possible states for our simulation), we were able to devise reasonable efficiency transition probabilities, based upon observations of performance loss curves by General Electric (1996). Again this is an area where integrated AI and statistical techniques using on-line sensor data, expertise and maintenance and repair log books would be appropriate (Kim 1995).

We began by dividing the range of possible efficiencies into four levels. Transition probabilities are nonzero for adjacent efficiency levels. Jumps across more than one efficiency level can be attributed to only decisions 4 or 5 (blade scouring or replacement). All efficiency levels return to 1 following choice of decision 5 (blade replacement). Efficiency loss within one period is due to lack of action (decisions 6 and 7). Choice of decision 4 (blade scouring) initially returns efficiency to level 1. However, non-recoverable degradation can eventually reduce that improvement. Results are recorded in Table 1.

	X(t+1) =	**1**	**2**	**3**	**4**
X(t)=					
1		>0; 1,2,4, 5,6,7	>0; 6,7	0	0
2		>0; 1,2,4,5	>0; 1,2,4, 6,7	>0; 6,7	0
3		>0; 4,5	>0; 1,2,4	>0; 1,2,4, 6,7	>0; 6,7
4		>0; 4,5	>0; 4	>0; 1,2,4	>0; 1,2,4, 6, 7

Table 1: Efficiency Transition Probabilities

Conclusions and Future Work

In this paper we have described ongoing research in the area of maintenance and warranty decision making for gas turbines used in power plants. We described and modeled economic issues related to warranty maintenance service from the perspectives of both the consumer (power plant owner) and producer (General Electric). Finally, we developed a dynamic programming approach to optimize maintenance activities and warranty period length suited in particular to compressor maintenance. Complete solution to the problem would involve simultaneously solving the consumer, producer, and optimal maintenance (dynamic programming) problems.

This dynamic program was devised to calculate the minimum expected maintenance costs for the remaining warranty time at every period during the warranty. The expected cost for the warranty period enables the producer to choose a reasonable price to charge the customer. Furthermore, the model tells the user which action to choose at the end of each period given engine status information like turbine efficiency and turbine state. The producer would then choose the decision whose expected maintenance cost for the remaining warranty is the minimum among all available options.

Future research on this topic would include a thorough sensitivity analysis of all user-input costs as well as the efficiency and state transition probabilities. These sensitivity analyses could be used to prioritize knowledge extraction efforts required to refine these parameters.

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