System Performance Based Inspection

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1 Introduction

Recently in many commercial fields, the market has become more competitive and demanding. Many monopolies have become extinct and the privatization process has accelerated. Even traditionally government owned companies, such as energy suppliers, have gone through the process of being opened to the public. These processes limit the potential margin and emphasize the need to achieve a faster and greater return on investment. As a result, the need to obtain and develop a means to decrease the operation cost and therefore increase the profit have been enhanced.

One of the main contributors to the operation costs is preventive maintenance activity. Several costs are associated with the preventive maintenance: first, the cost of the needed repair team and tools. Also, spare parts are needed in case a replacement is required during preventive maintenance. Lastly, during maintenance, the system is offline and thus accumulates downtime. However, the preventive maintenance should decrease the risk of having an unexpected event that will cost more than the preventive maintenance costs.

This article presents a method to calculate the most cost-effective preventive maintenance strategy, based on the overall system behavior and its expected future performances.

2 The Questions

Two main questions are asked when trying to obtain the best preventive maintenance strategy: 1) When to perform the inspection? and 2) What to do during the scheduled inspection?

It is apparent that these two questions are closely related, and thus cannot be referred to individually. The first question (when?) must be answered before we can answer the second question (what?), since the decision regarding the inspection scope depends on the inspection time. If the inspection is postponed, we will most likely need to replace more aged components. Whereas, performing the inspection at an earlier date might result in replacing fewer components. In addition, we need to keep in mind that the objective when dealing with these questions is to optimize the total operation costs, thus the entire operation must be accounted for.

The question “when?” is indeed a conglomerate of several questions, such as: What should be the frequency of inspections? What is the best interval between two sequential preventive maintenance actions? Should we shift the planned inspection date due to a nearby unscheduled event? …etc. When answering these questions we should also take into account the different time axises, in many industrial fields the operation time axis is not given in calendar time, but in an equivalent operation time.

Also, the second question, “what?”, represents several different question, such as: which components should be inspected?; what should be the criteria for replacing an inspected part?; should the replacement be on a part level or on an assembly level (in order to save the disassembling time)?; should we repair or replace parts?; etc.

3 Aging and Maintenance

The behavior of a part whose lifetime follows a non-exponential distribution depends on how long the part has already been operating, since it is aged. The age of a part is defined as the probability that it will undergo an event, such as failure or exceeding a detrition threshold point, sometime between its birth date up to the current time. In other words, it's the Cumulative Density Function (CDF) of the part.

The system, being composed of many parts with relationships between them, is also aging. The aging of the system can also be expressed as the system cumulative density function, but can not be analytically calculated in most cases [1].

Since the system is aged, it will reach a point in time when the risk of having a system failure is too high. The aim of the preventive maintenance is to capture that point (when?) and then to decrease the system age to an acceptable level. Looking at the graph illustrated in Figure 1 below, one can see the resembling saw-tooth curve that characterizes the preventive maintenance effect on the system age.

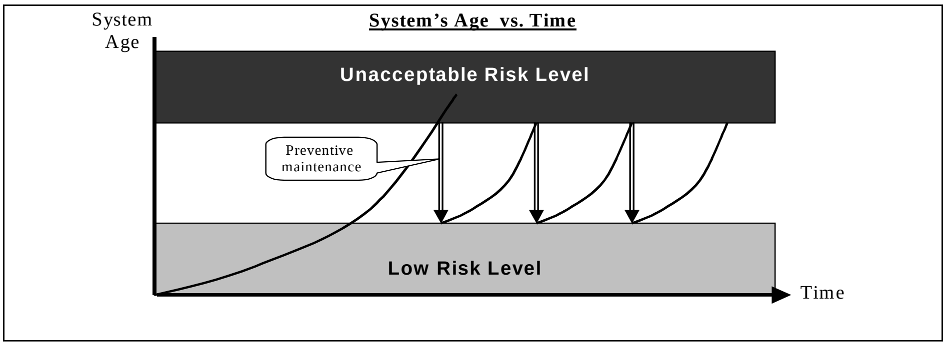

Figure 1: Preventive Maintenance Age Curve

It can be concluded that in order to solve the 'preventive maintenance worthiness' mystery, one must first understand the system's future behavior across the time. It should be noted that it is not the average behavior (calculated for example, by the Markov methods) that is required, but the actual time dependent behavior. Essentially, we need to know the system failure distribution as a function of time, where the term 'system failure' should be clearly defined according to the purpose of the inspection, as will be discussed below.

4 How to Define the System Failure

In order to decide when to perform an inspection we must know the system's future behavior as a function of time, and the risk we are willing to take. The former being purely mathematical, while the latter results from a management decision, coinciding with economical logic, contractual liabilities and other business rules.

In order to learn the system behavior in the future we must first define the term – 'system failure'. This term should be based on the structure of the system and on the nature of its parts as illustrated in the examples below:

1. A **control system** for the cooling water pump of a power station. This system is comprised of a number of elements that, due to the importance of the system, are constructed in an arrangement of 2 out of 3. Any circumstance in which two elements are not functioning results in a failure report. In this system we can plan the inspection in order to avoid the risk of losing the entire control system, i.e. two concurrent failures, or we can be even more conservative and plan it to decrease even the risk of a single component failure.
2. A **process system** consisting of a number of sequential processes. In this case, failure of one process will lead to a system failure and the production will terminate.

3. A **production system** in which every parallel branch contributes a certain percentage of the total throughput. In such a system, loss of capacity can be tolerated to a certain extent. In this case, a system failure can be defined as the point when the production level decreases below a certain threshold.

The above examples describe different types of system functions that define the system malfunctioning. However, every system is composed of components whose failure can cause the system to fail. Therefore, it is also important to allow flexibility when defining the single component failure. The definition of the component failure function must match its maintenance specification. Two examples for demonstrating this are as follows:

1. A simple component that exists in one of the following two states - either functioning or malfunctioning. In this case, the failure function should describe its transition from the functioning state (up) to the malfunctioning one (down).
2. A component with several operation levels. For such a component, the failure function should be described as exceeding a certain degradation threshold. For example, a burner component, for which the thermal efficiency is critical, was found to have a declining efficiency with the loss of its ability to resist the heat, as a result of thinning of its thermal isolation. In this case, the failure is defined as the wearing out of the isolation layer below the certain thickness.

5 The Proposed Method

The method proposed in this paper is a hybrid of the Monte Carlo simulation and analytical calculation. This kind of hybrid method allows us to benefit from the accuracy of the analytical calculation and the power of the Monte Carlo simulation to capture real life phenomena such as aging and inter relations between components of a complex systems.

Simulating the system operation enables us to obtain the future behavior of the system as a function of the time, and based on that, we can build the system's survival curve. This curve represents the probability that the system will survive up to a given time. Note that the complementary curve is the system's risk curve.

Knowing the survivability of the system, one can set up a survival threshold for the system. The preventive maintenance date driven from that threshold is the date when the system survival curve reaches this threshold.

Once the preventive maintenance date has been set, we can now calculate several indices that represent the health condition of the equipment at that chosen inspection date. Many possible metrics can be calculated here to assist in making the decision to replace the part or not. Some of these are based on the simulation results, but most of them are analytically calculated. For example we can calculate the:

- Probability of failing prior to that inspection date.
- Probability to survive another preventive maintenance interval.
- Relative contribution to the system downtime.
- Number of failures.

Based on these characteristics, and the known cost of part replacement, a business rule to decide whether to replace a part or not can be established. Such a rule can be, for example, replacing every part whose "risk-cost" is higher than its "replacement cost", and whose chance of survival to the next interval is lower than 5%. In that case the "risk-cost" is the cost of having a system failure due to this part times the probability that it will fail up to the next preventive maintenance date, and the "replacement cost" is the cost of refurbishing this part plus the cost of additional schedule downtime that results from its replacement.

6 Example

Consider the system shown in Figure 2, this system consists of 25 parts of 9 different types. The failure and repair data for all the types is given in Table 1, for the Weibull distribution P1 is the scale parameter and P2 is the shape parameter. For Exponential distribution P1 is the MTTR, for Normal distribution P1 represents the mean and P2 the standard deviation, and for Log-Normal distribution P1 and P2 are the mean and the standard deviation of the corresponding normal distribution [1]. All components are repaired on site and no turnaround time is considered.

SPAR^{TM} software, a multi purpose Monte Carlo simulation tool, was utilized to predict the behavior of this system in the future, starting from the beginning of the year 2004. An initial age, representing the time that has passed since the replacement of each part, was assigned to each part. The system operates only 12 hours a day. Using the simulation engine, 10,000 different future possibilities (histories) of the system were built. In each history we recorded the time when the first system failure occurred, and the component that caused it.

Based on the collected simulation information, we calculated a histogram of the system failure time, i.e. the number of system failures that occurred at each time interval. We also drew the cumulative system survival probability, which represents the chance that the system will not fail up to a time point. These two are shown in Figure .

If we wish to design the system to survive with probability of 95% (i.e. only 5% risk of having a system failure can be tolerated) the preventive maintenance date must not be later than June 20th, 2004.

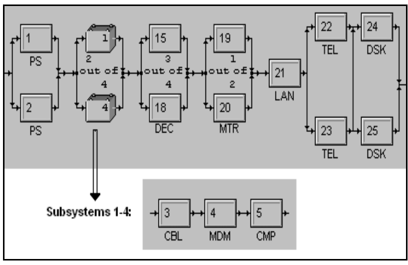

Figure 2: The System RBD

Type	Failure			Repair		
	Distr.	*P1*	*P2*	*Distr.*	*P1*	*P2*
PS	Weibull	2.36E-05	1.23	Normal	10	4
CBL	Weibull	2.15E-09	2.34	Exponential	24	
MDM	Weibull	1.58E-10	3.01	Normal	12	3
CMP	Weibull	4.69E-05	1.34	Normal	3	0.6
DEC	Weibull	1.26E-07	2.04	Exponential	4	
MTR	Weibull	1.70E-06	1.73	Normal	14	4.5
LAN	Weibull	2.31E-11	2.028	Exponential	1	
TEL	Weibull	1.42E-10	2.275	Log-Normal	12	5
DSK	Weibull	1.22E-09	2.6	Exponential	24	

Table 1: Failure and Repair Data

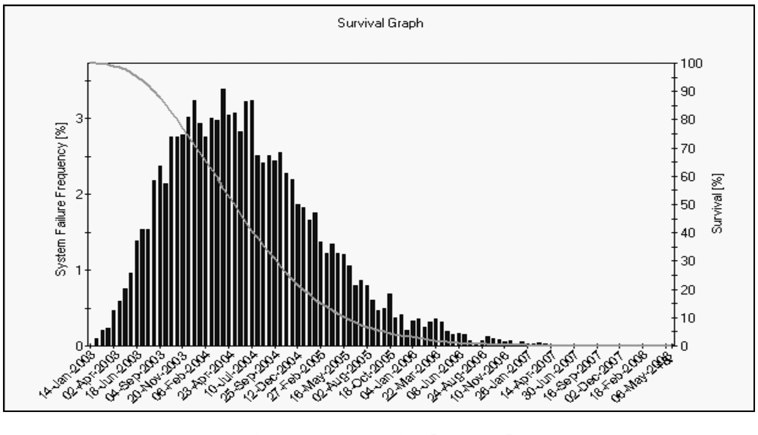

Figure 2:Survival Graph

After having set the inspection date, we now need to decide what to do during the inspection. Based on the simulation results we can draw the contribution of each part and of each part-type to the system risk (the chosen 5%), as shown in **Figure 3 - A and B**. These criticality charts allow us to identify the distribution of the risk and make sure that only a small portion of the risk is contributed by critical parts.

A matrix, consisting of several metrics, can be used to diagnose the health condition of the components. These metrics can be analytically calculated and can include, for example:

- the probability of each part to fail prior to the inspection date, this is the CDF of the part up to that time – [F(Inspection-Date)].
- The probability to survive up to the inspection date. This is the complementary of the CDF up to that time – [1-F(Inspection-Date)].
- The chance to survive another period (P). This is the conditional probability for surviving up to the next internal (P), given that it survived up to the inspection date - [$\frac{1-F(P)}{1-F(Inspection-Date)}$].

Based on these metrics, and the cost of failure and repair, one can decide which parts should be replaced and which should remain in the system for another preventive maintenance interval.

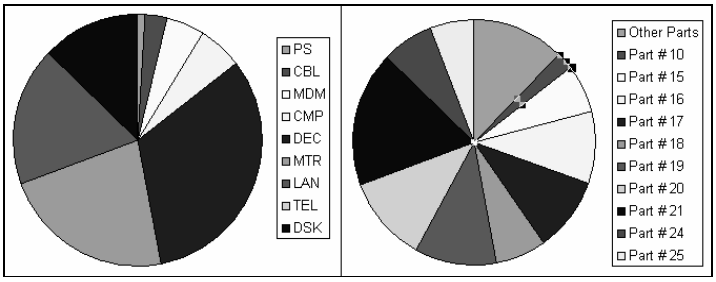

Figure 3: A-Part Criticality B-Type Criticality

7 Conclusion

The paper presents a method to schedule preventive maintenance and sets the scope of work during this preventive maintenance based on the system performances. This method utilizes a Monte Carlo simulation to predict the future behavior of the system and thus set an acceptance threshold for the system survivability that will dictate the inspection schedule. Then a matrix of different indices that represents the health condition of the system's parts is calculated analytically. This matrix of indices will assist in the definition of which parts should be replaced and which can remain in operation until the next preventive maintenance activity.

References

1. Dubi A. Monte Carlo Applications for System Engineering. John Wiley & Sons, UK, 1999
2. SPAR User's Manual, Clockwork Solutions Inc. Austin USA, 2000.