On Determining Optimal Inspection Interval for Minimizing Maintenance Cost

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SUMMARY & CONCLUSIONS

The majority of system failures do not occur without any warning signs. This is especially true for failures caused by degradation. By examining the failure-critical indexes during scheduled inspections, actions can be taken to address degraded components and prevent big losses due to failures.

In this paper, we assume that an imminent failure can be noticed when an inspection is conducted during a short time period right before the failure. Clearly, by conducting frequent inspections, failures can always be detected and prevented. However, the total inspection cost will be very high if the inspection interval is too short. On the other hand, if the inspection interval is too long, a coming failure may not be effectively detected and the total cost due to failures will be high. Therefore, an optimal inspection interval balancing these two costs needs to be identified.

A model for determining the optimal inspection interval to minimize the maintenance cost is proposed in this paper. The analytical solution of the model is provided and compared with simulation results. The proposed method is especially useful for process industries such as oil and gas refineries, food processing and pharmaceutical manufacturing. By conducting optimal inspections for components with degradation characteristics, failures will be prevented, maintenance cost will be reduced and the process throughput can be improved.

1 INTRODUCTION

Preventive replacement and periodical inspections are two major approaches used for improving system availability and reducing maintenance cost. Preventive replacement replaces a system/component/unit at a certain time interval or at a failure, depending on which one is earlier. A great deal of work has been done on inspection and preventive maintenance strategies [1, 2, 3]. Most of the published papers on inspection strategies focus on finding hidden failures. Hidden failure refers to the case where a failure remains undiscovered unless an inspection or a test is performed [4]. The interval between two successive inspections is therefore called the *failure finding interval*. There are two types of hidden failures in general:

- Type I: Protective devices or standby unit. The function of these devices is to protect the main system in case of failures. Safety devices, emergency devices, standby units are this type of hidden failure devices [5]. Their failure will not cause direct loss if they are not needed.
- Type II: Operating devices. Underground pipes and underwater equipment are this type of devices. They are operating systems, and their failure will cause direct loss.

Different from the above mentioned hidden failures, some failures can be detected even before they happen. For example, a long crack length on a shaft or a thinning connector line is an early sign of an imminent failure. This type of failures is called *revealed failures*. In this paper, we will focus on preventing revealed failures using inspection, rather than finding hidden failures as in the published papers [1, 5, 6-10]. This inspection strategy is especially useful for failures caused by degradation. Units that are going to fail soon will be replaced or repaired at inspection if there is evidence of an oncoming failure. For example, if a failure is going to happen at time 100, an inspection at time 20 may not be able to detect it since the signs of the coming failure may not be strong enough. However, if an inspection is conducted at time 95, then we should see strong evidence that the component is going to fail soon.

Therefore, a failure detection criterion for a device needs to be established based on engineering knowledge. It could be a fixed time period such as an inspection that is conducted within 10 hours before the occurrence of failure. It also can be a fixed percentage of life consumption such as an inspection that is conducted after 90% of the failure times. In this paper, we will use the percentage criterion. The value of the percentage can be determined based on engineering knowledge. Past failure information and warning signs such as degraded performance of a component, increasing temperature or vibration level can help engineers determine a reasonable percentage value.

To better understand the failure detection criterion based on percentage of life, let's define the failure time as t for the unit under consideration, and p as the fixed percentage. If an inspection is conducted in interval [$p \cdot t$, t], then the failure will be noticed before it occurs. Therefore interval [$p \cdot t$, t] is called *failure detection zone*.

If an inspection is conducted within a failure detection zone, then the coming failure will be noticed. Otherwise, a failure will not be noticed during inspection and it will occur later. These two scenarios are illustrated in Figure 1, where x, $2 \cdot x$, and $k \cdot x$ are the scheduled inspection points.

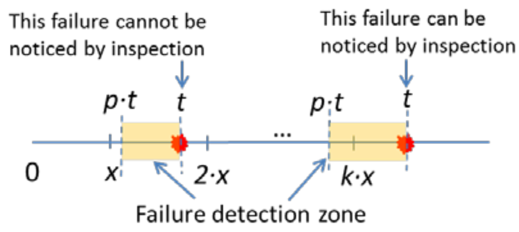

Figure 1 – Inspection for Detecting a Coming Failure

In Figure 1, the red star is the failure time t. The yellow shaded area is the failure detection zone.

The paper is organized as follows. In section 2, two models will be proposed. One model is for determining the optimal inspection interval for minimizing the *long term maintenance cost* per unit time. The other model is for the optimal inspection interval to minimize the cost per unit time in one inspection renewal cycle, called *short term maintenance cost*. Section 3 gives examples of using the proposed method. Simulation results will be used to validate the analytical solutions. Section 4 concludes the paper.

2 OPTIMAL INSPECTION FOR DETECTING COMING FAILURES

Two objectives are usually considered when determining an optimal inspection interval. They are: 1) improving the system availability, and 2) minimizing the maintenance cost. In this paper, our purpose is to minimize the maintenance cost. The following assumptions are used:

- Inspection intervals are based on system (or component) age (such as mileages, hours of operation), not calendar time.
- Failure time is a random variable following a cumulative distribution function $F(t)$.
- The time required for inspection is negligible.
- If an inspection is within a certain percentage p $(0 < p < 1)$ of a coming failure time, then the system will be replaced and the failure is prevented.
- A failure will be noticed right away when it occurs.
- System is replaced either at failure or at inspection if the inspection time meets the failure detection criterion.
- The time for replacing a system under inspection is negligible.
- An inspection will not affect the age of the system.
- A new cycle starts (the system is renewed) when the system is replaced.
- Inspections do not introduce failures.

For a given inspection interval x, the first question arising is the probability of noticing a coming failure. If the probability is very low, then we need to select a smaller x to increase the chance of detecting coming failures.

2.1 *Calculate the Probability of Noticing a Coming Failure*

From Figure 1, it is clear that if $p \cdot t \le k \cdot x \le t$, or in other words, if a failure time meets the following condition:

$$k \cdot x \le t \le \frac{k \cdot x}{p}, \tag{1}$$

then failure will be noticed in advance. Equation (1) can be illustrated in Figure 2.

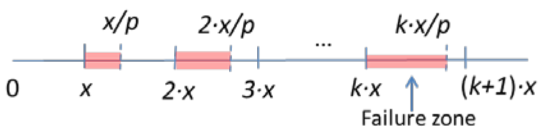

Figure 2 –Failure Zones for Detectable Failures

The shaded area in Figure 2 is called *failure zone* for detectable failures. There are two cases for failure zones:

- Case 1: This case is shown in Figure 2, where $kx/p < (k+1)x$. It means that there is no overlap between the kth and the (k+1)th failure zones for noticeable failures. Failures that fall in the failure zones will be noticed. For case 1, we have:

  $$kx/p < (k+1)x.$$

  That is:

  $$k < \frac{p}{1-p} \tag{2}$$

  Therefore, inspections with numbers less than $p/(1-p)$ belong to case 1.
- Case 2: This is the case where $kx/p \ge (k+1)x$. It means that the kth and the (k+1)th failure zones are overlapped and so do all later failure zones. Therefore, any failures occurring after $k \cdot x$ will always be noticed through inspection, and the system will be replaced at inspection. Similar to case 1, inspections with numbers larger than or equal to $p/(1-p)$ belong to case 2.

In case 1, the probability of noticing a failure before it occurs is:

$$P_1 = F\left(\frac{kx}{p}\right) - F(kx) \tag{3}$$

where $F(\cdot)$ is the cumulative distribution function for the failure time of the system. It is assumed to be known.

Define M as the largest integer less than $p/(1-p)$:

$$M = \begin{cases} \frac{p}{1-p} - 1 & \text{if } \frac{p}{1-p} \text{ is an integer} \\ \left\lfloor \frac{p}{1-p} \right\rfloor & \text{if } \frac{p}{1-p} \text{ is not an integer} \end{cases} \tag{4}$$

The probability of noticing a failure before it occurs for case 2 is:

$$P_2 = 1 - F\left[\left(M+1\right)x\right] \quad (5)$$

From Equations (3) and (5), we can obtain the combined probability of noticing a coming failure:

$$P = \sum_{k=1}^{M}\left(F\left(\frac{kx}{p}\right) - F\left(kx\right)\right) + 1 - F\left[(M+1)x\right] \quad (6)$$

From Equation (6), we can see that if $x \to 0$, the probability of noticing a failure before it occurs is 1. This is true because if the inspection interval x is 0, then the system is being inspected continuously. If $x \to \infty$, then no inspection is conducted and the probability of noticing a coming failure is 0.

2.2 *Optimal Inspection Interval Criteria*

There are two commonly used criteria for determining an optimal inspection interval. One is for minimizing the average cost within one inspection cycle, and the other is for minimizing the long term average cost.

Let's use an example to explain the differences between these two. Assume a failure of a component can be detected any time after 90% of its life has been consumed. Inspections are scheduled every 20 hours of operation. A failure will cost \$50. An inspection will cost \$5 and a preventive replacement will cost \$20. Now assume a new component failed after 18 hours of operation. Since the failure occurs before the first inspection which is at 20 hours, the failure cannot be prevented. Therefore, the length of this replacement cycle is 18 hours, and the cost is \$50. The failed component is replaced with a new one and a new cycle started. Assume this newly installed component will fail at 21 hours. 90% of its life is 18.9 hours. Since the scheduled inspection is at 20 hours of operating, which is between 18.9 and 21, the failure will be noticed before it occurs. The component is replaced at 20 hours. The cost of this inspection is \$25 (inspection cost + preventive replacement cost) and the length of this cycle is 20 hours.

The average cost per unit time in one cycle is calculated as follows. The cost per time for the first replacement cycle is \$50/18 = \$2.7778/hour; the cost per time for the second replacement cycle is \$25/20 = \$1.25/hour. The average cost per unit time in one cycle is the average of these two. It is (\$2.7778+\$1.25)/2 = \$2.0139/hour.

The long term average cost is the total cost divided by the total operation time. This is (\$50+\$25)/(18+20) = \$1.974/hour. This is the same as the average cost per cycle divided by the average length of one cycle, if you divide both the numerator and denominator by 2. The formulas for the two cost rates are given next.

For a given renewal (replacement) cycle, the e*xpected average cost rate in one cycle* is:

$$C_S(x) = \text{Expected}\left(\frac{\text{Cost in one cycle}}{\text{Time of one cycle}}\right) \quad (7)$$

Equation (7) is the expected one cycle cost rate, or the *short term cost rate*. It is used when different components are expected to be used over an operation period, and its purpose is to minimize the cost per unit time over one replacement cycle only.

The *expected long term cost rate* with an inspection time interval of x can be calculated based on the renewal reward process theory, and it is

$$C_L(x) = \frac{\text{Expected cost in one cycle}}{\text{Expected time of one cycle}} \quad (8)$$

The *long term cost rate* in Equation (8) is used when the same optimal inspection interval and the same type of components are planned to be used for a long time.

Our objective is to find an optimal inspection interval x to minimize either the long term cost rate or the short term cost rate. The following three cost types are considered in the calculation:

- C_P is the cost if a coming failure is noticed before it occurs. This is the cost of a preventive replacement.
- C_F is the cost if a failure occurs without being noticed during previous inspections. This is the cost of a failure replacement.
- C_I is the cost of conducting one inspection.

Clearly, the cost of preventing replacement should be less than the cost in case of a failure, so C_P should be less than C_F. The cost of conducting an inspection should also be less than the cost of a failure replacement, so C_I should be less than C_F.

In the following sections, we will present models for minimizing the short term cost rate and a model for minimizing the long term cost rate.

2.3 *Optimal Inspection Interval for Minimizing Short Term Cost Rate*

If a failure occurs before the first inspection, it will never be noticed through inspection, so the cost rate for this failure is:

$$C(x) = \frac{C_F}{t}, \qquad \text{when } 0 \le t < x \quad (9)$$

From section 2.1, we know that if a failure occurs in the first detection zone, it can be noticed by the first inspection, so the cost rate for this failure is:

$$C(x) = \frac{C_P + C_I}{x}, \qquad \text{when } x \le t < \frac{x}{p} \quad (10)$$

We also know that if a failure occurs between the first and the second detection zone, then it cannot be noticed by inspection, so the cost rate for this failure is:

$$C(x) = \frac{C_F + C_I}{t}, \qquad \text{when } \frac{x}{p} \le t < 2x \quad (11)$$

The inspection cycle restarts whenever the system is replaced. The general formulas for the cost rate within a renewal cycle are given next.

- Case 1: When $k \le M$, the detection zones do not overlap. Some of failures will be detected before they occur but not all. When a failure is in the *k*th detection zone, it will be detected. The cost rate is:

$$C(x)=\frac{C_P+kC_I}{kx}, \qquad \text{when } kx \le t < \frac{kx}{p} \tag{12}$$

When the failure is between the kth and the (k+1)th detection zone, it will go unnoticed, so the cost rate is:

$$C(x)=\frac{C_F+kC_I}{t}, \qquad \text{when } \frac{kx}{p} \le t < (k+1)x \tag{13}$$

- Case 2: When $k \ge M+1$, the detection zones are overlapped. All failures occurring in or after the (M+1)th detection zone will be detected in advance. When a failure occurs in the (M+1)th detection zone, the cost rate is:

$$C(x)=\frac{C_P+(M+1)C_I}{(M+1)x}, \quad \text{when } (M+1)x \le t < (M+1)\frac{x}{p} \tag{14}$$

When a failure occurs between the end of the (M+1)th detection zone and the end of the (M+2)th detection zone, the cost rate is:

$$C(x)=\frac{C_P+(M+2)C_I}{(M+2)x}, \quad \text{when } (M+1)\frac{x}{p} \le t < (M+2)\frac{x}{p}, \tag{15}$$

and so on for all larger values of k.

Combining the formulas of case 1 and case 2, the final cost rate function in one cycle becomes:

$$C_S(x)=\int_0^x \frac{C_F}{t} f(t)dt+\sum_{k=1}^{M}\left[\int_{kx}^{\frac{kx}{p}} \frac{C_P+kC_I}{kx} f(t)dt+\int_{\frac{kx}{p}}^{(k+1)x} \frac{C_F+kC_I}{t} f(t)dt\right]$$
$$+\int_{(M+1)x}^{\frac{(M+1)x}{p}} \frac{C_P+(M+1)C_I}{(M+1)x} f(t)dt+\sum_{k=M+1}^{\infty}\int_{\frac{kx}{p}}^{\frac{(k+1)x}{p}} \frac{C_P+(k+1)C_I}{(k+1)x} f(t)dt \tag{16}$$

The only unknown in Equation (16) is the inspection interval x. The value of x that minimizes $C_s(x)$ can be found numerically. However, the simplest way for finding an approximated solution is to plot the cost vs. x curve. The optimal x can then be identified from the curve.

2.4 *Optimal Inspection Interval for Minimizing Long Term Cost Rate*

The long term cost rate is calculated from Equation (8). From the previous section we know that when the inspection interval is x, the expected length for a renewal cycle is:

$$E\left(\text{Cycle Length} \mid x\right)=$$
$$\int_0^x tf(t)dt+\sum_{k=1}^{M}\left[\int_{kx}^{\frac{kx}{p}} (kx) f(t)dt+\int_{\frac{kx}{p}}^{(k+1)x} t f(t)dt\right] \tag{17}$$
$$+\int_{(M+1)x}^{\frac{(M+1)x}{p}} \left[(M+1)x\right] f(t)dt+\sum_{k=M+1}^{\infty}\int_{\frac{kx}{p}}^{\frac{(k+1)x}{p}} \left[(k+1)x\right] f(t)dt$$

Equation (17) takes the denominator of each term in equation (16).

The expected total cost in a renewal cycle is:

$$E(\text{Total Cost in One Cycle} \mid x)=\int_0^x C_F f(t)dt$$
$$+\sum_{k=1}^{M}\left[\int_{kx}^{\frac{kx}{p}} \left[C_P+kC_I\right] f(t)dt+\int_{\frac{kx}{p}}^{(k+1)x} \left[C_F+kC_I\right] f(t)dt\right]$$
$$+\int_{(M+1)x}^{\frac{(M+1)x}{p}} \left[C_P+(M+1)C_I\right] f(t)dt \tag{18}$$
$$+\sum_{k=M+1}^{\infty}\int_{\frac{kx}{p}}^{\frac{(k+1)x}{p}} \left[C_P+(k+1)C_I\right] f(t)dt$$

Equation (18) takes the numerator of each term in equation (16). So the long term cost rate is:

$$C_L(x)=\frac{E(\text{Total Cost in One Cycle} \mid x)}{E\left(\text{Cycle Length} \mid x\right)} \tag{19}$$

The only unknown in Equation (19) is the inspection interval x. The value of x that minimizes $C_L(x)$ can be found either numerically or graphically, similar to the previous case.

3 EXAMPLES

Two examples will be given in this section. The first is for the short term cost optimization, and the second is for the long term cost optimization.

3.1 *Example for Optimal Inspection Interval for Minimizing Short Term Cost Rate*

Problem Statement: Assume a component is used in a manufacturing process and it needs to be replaced periodically. The following information is provided: the average cost per inspection is \$10. If an imminent failure is noticed at inspection, the replacement cost for the component is \$200. However, if a failure happens, the cost will be \$1,000. The failure detection threshold is 90% of the failure time. It is also known that the failure time distribution of this component is a Weibull distribution with $\beta=2$ and $\eta=500$ hours. Find the optimal inspection interval that will minimize the short term (one cycle) cost.

Analytical Solution: Applying Equation (16) with different inspection interval x and conducting calculations using Mathcad, we get the results shown in Table 1.

Table 1 – Results for Short Term Inspection Cost and Failure Detection Probability

Inspection Interval x (hour)	**Short Term Cost Rate ($/hr)**	**Detection Probability**
5	2.915	0.9967
10	2.077	0.9869
15	1.89	0.9709
20	1.867	0.9494
25	1.906	0.9229
30	1.973	0.8924
35	2.052	0.8587
40	2.135	0.8227
45	2.218	0.7854
50	2.299	0.7475
55	2.376	0.7098
60	2.448	0.6729

The first column is the inspection interval *x* while the second column is the long term cost rate for the corresponding value of *x*. It is clear that when the inspection interval is about 20 hours, the expected long term cost rate is minimal. The results in Table 1 also are presented in Figure 3.

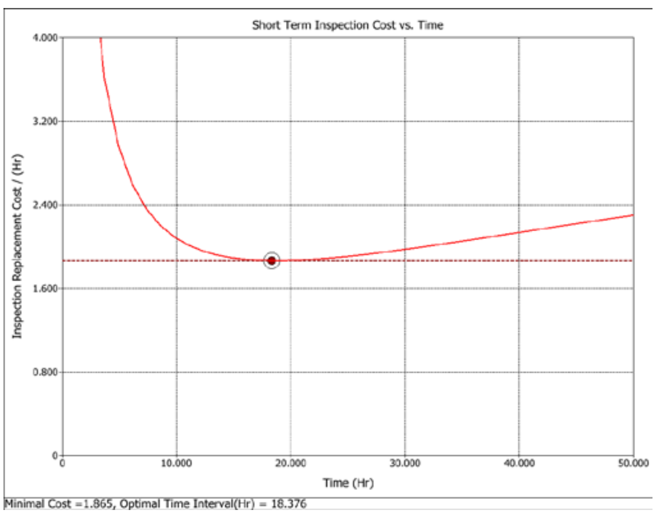

Figure 3 – Plot for the Short Term Inspection Cost

Figure 3 shows that the exact optimal inspection interval is 18.376 hours long and the corresponding cost is $1.865 per hour (the red dot with a circle on the plot). Since the cost at 20 hours is almost the same as at the optimal solution, we can consider 20 as the optimal inspection interval.

Equation (6) gives the probability of detecting an imminent failure by inspection. Since the detection threshold for the consuming life is 90%, we have:

$$M = \frac{p}{1-p} - 1 = \frac{0.9}{0.1} - 1 = 8$$

and from Equation (6), we get:

$$\begin{aligned} P &= \sum_{k=1}^{M} \left(F\left(\frac{kx}{p}\right) - F(kx) \right) + 1 - F\left[(M+1)x\right] \\ &= \sum_{k=1}^{8} \left(F\left(\frac{20k}{0.9}\right) - F(20k) \right) + 1 - F\left[180\right] \\ &= 0.9494 \end{aligned}$$

This is the probability of noticing an imminent failure when the inspection interval is 20 hours. The detection probabilities for different inspection intervals are also given in the third column of Table 1.

Simulation Results: The above analytical solutions are validated using simulation. 25,000 simulations were conducted using an inspection interval of 20 hours. One simulation ends whenever a system is replaced, either at a failure or at an inspection if the imminent failure is detected. In each simulation, a failure time is generated first. Assume a generated failure time is 51.44, then we know its failure detection zone is [46.296, 51.44] because $51.55 \times 0.9 = 46.296$. Since the inspection interval is 20, no multiples of 20 are included in this interval, therefore no inspection is scheduled within this detection zone. This simulation (inspection cycle) ends at 51.44, the failure time. The cost for this cycle is the cost of the failure plus the cost of the two inspections conducted at time 20 and 40. It is $\$1,000 + 2 \times \$10 = \$1,020$. The cost per unit time for this cycle is $\$1,020 / 51.44 = \$19.83$.

If for another simulation the generated failure time is 318.5, then the failure detection zone is [286.65, 318.5]. A scheduled inspection at time 300 is in this detection zone, so this simulation (inspection cycle) ends at 300. The unit is replaced at time 300, and the failure at 318.5 is prevented. The cost for this cycle is the cost of the replacement plus the cost of the 15 inspections conducted during this cycle. It is $\$200 + 15 \times \$10 = \$350$. The cost per unit time for this cycle is $\$350 / 300 = \$1.1667$.

Repeating the above process 25,000 times by generating 25,000 failure times, 25,000 cost per unit time in one cycle will be obtained. Taking the average of them, the final simulated average short term cost per hour is $1.868.

To get the simulated failure detection probability, we can divide the number of simulations that end at inspection by the total number of simulations of 25,000. The obtained value is 0.9505. Both the cost and the detection probability are very close to the analytical results of $1.867 and 0.9494. The simulation results support that our proposed method is correct.

3.2 *Example for Optimal Inspection Interval for Minimizing Long Term Cost Rate*

For the same example as in the previous section 3.1, we also can calculate the long term cost for different inspection intervals, if the same component is planned to be used for a long period of time.

Analytical Solution: Applying Equations (17-19) with different inspection interval *x* and conduct the calculation in Mathcad, we get the average long term inspection costs, which are given in Table 2.

Table 2 – Results for Long Term Inspection Cost

Inspection Interval *x* (hour)	Long Term Cost Rate ($/hr)
5	2.511
10	1.521
15	1.216
20	1.088
25	1.036
30	1.024
35	1.038
40	1.067
45	1.106
50	1.152
55	1.201
60	1.252

We can see that when the inspection interval is about 30 hours, the expected long term cost rate is minimal. The results in Table 2 are also illustrated in Figure 4.

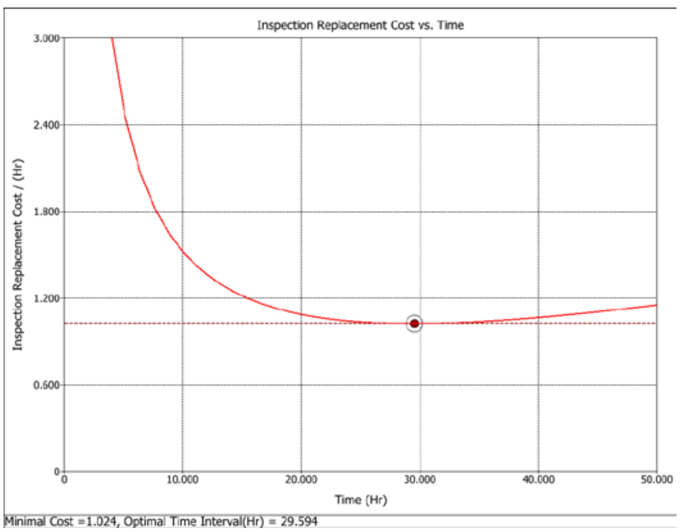

Figure 4 – Plot for the Long Term Inspection Cost

Simulation Results: The above analytical solutions are validated using simulation. 25,000 simulations were performed using an inspection interval of 30 hours. The simulation process is the same as the one used for the short term cost. The only difference is how the cost per unit time is calculated, as explained at the beginning of section 2.2. The calculated long term cost per hour from the simulation results is $1.025. This result is very close to the analytical result of $1.024. The simulation result supports that our proposed method is correct.

4 CONCLUSIONS

Periodical inspection and preventive maintenance are two commonly used strategies for reducing maintenance cost and improving system availability. Optimal replacement by periodical preventive maintenance has been extensively studied in the past [1-5]. Optimal inspection interval for detecting hidden failures that have occurred is also studied [6-10]. However, little work has been done on optimal inspection for detecting an imminent failure and preventing it. In this paper, we proposed two models for determining optimal inspection intervals. Numerical examples show that the proposed analytical methods are correct since the results match the simulation results very well.

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