PREVENTIVE MAINTENANCE OPTIMIZATION UNDER DETERIORATION

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Özet: Önleyici bakım, yıpranma sonucu zamanla performansı bozulan bir ekipmanın hazır bulunabilirliğini arttırmak veya bakım maliyetlerini azaltmak için kullanılabilir. Düzenli muayeneler sayesinde, ekipmanın durumu belirlenerek önleyici bakım daha etkin kullanılabilir. Buna aynı zamanda durum-tabanlı bakım da denir. Bu çalışmada, yıpranmaya maruz kalan bir ekipman için Markov zincirlerine dayanan bir durum-tabanlı bakım modeli önerilmektedir. Kesikli yıpranma aşamaları olarak düşünülen sistemin yıpranma seviyeleri, düzenli muayenelerle ölçülebilmektedir. Hazır bulunma maksimizasyonu veya bakım maliyeti minimizasyonu amaçları doğrultusunda model için optimal çözümler önerilmiştir.

Anahtar Kelimeler: Önleyici bakım, Hazır bulunma, Markov zincirleri, Yıpranma, Güvenirlik

Abstract: Preventive maintenance can be used to improve the availability or to decrease the repair costs when a device performance gets worse by deterioration. With the help of inspection, the condition of the device can be assessed. Thus, preventive maintenance can be used more efficiently. This is what is known as condition-based maintenance. In this paper, we proposed a condition-based maintenance model by using Markov chains for a device under deterioration. The system is considered as discrete stage deterioration and the first stage is the good stage. By periodic inspections, system's deterioration state is exposed perfectly. Depending on the availability maximization and maintenance cost minimization, optimal solutions of the model is derived.

Key Words: Preventive maintenance; Availability; Markov chains; Deterioration; Reliability

I. Introduction

In today's world, not only the competitiveness but also the input prices have increased and obtaining the resources has become a critical issue. As a result, many firms have faced bottlenecks to continue their production operations. To overcome them, maintenance operations are as important as using the inputs effectively and efficiently. Efforts have been directed towards optimization of production systems in order to have better utilization of resources and to become cost-effective.

In the past, maintenance problems received little attention and researches in this area didn't have much impact. Today, this fact is changing because of the increasing importance of the role of maintenance in the new industrial environment. Maintenance, if optimized, can be used as a key factor

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in organization's efficiency and effectiveness. It also enhances the organization's ability to be competitive and to meet its stated objectives (Ben-Daya etc., 2000: 3-4).

Maintenance is a function in an organization that operates in parallel with production. The primary output of production is the desired product and its secondary output is demand for maintenance, which is in turn an input for the maintenance function. Maintenance results in a secondary input to production in the form of production capacity. While production manufactures the product, maintenance produces the capacity for production. Therefore maintenance affects production by increasing production capacity and controlling the quality and quantity of output (Ben-Daya and Duffuaa, 1995: 20–26).

Practically all components of an operations system are subject to deterioration and occasional failure in performing their assigned tasks. How fast deterioration occurs and how frequently breakdowns force idleness on workers, equipment and perhaps the entire process depends on the design of the process and operation conditions. Poor maintenance can result in defective output, unsafe working conditions and increased production costs due to repairs and excessive downtime (Dervitsiotis, 1981: 693). One way to reduce the cost of operation and production is to optimize utilization of maintenance resources (Duffuaa and Al-Sultan, 1997: 163–176).

Maintenance of equipments has significant impact on production costs. This is the one of the reasons why maintenance should not be underestimated.

II. Maintenance Strategies and the Maintenance Function

Effective maintenance is critical to many operations. It extends equipment life, improves equipment availability and retains equipment in proper condition. Conversely, poorly maintained equipment may lead to more frequent equipment failures, poor utilization of equipment and delayed production schedules. Misaligned or malfunctioning equipment may result in scrap or products of questionable quality. Finally, poor maintenance may mean more frequent equipment replacement because of shorter life (Swanson, 2001: 237–244).

Maintenance actions can be classified in two main categories; the first one is maintenance, in which actions are done before equipment or machine is broken to prevent any kind of failure; and the second one is repair, which is done after a failure occurs to restore the machine to the working condition.

Actually maintenance and repair are two supplementary functions, but the main function is maintenance. The inevitable failures which occurred in spite of the maintenance are fixed with repair. As is known, failures can be seen in every machine but the aim is to minimize these failures.

Many authors have described different strategies for maintenance management. Bateman (1995: 19–21) described three basic types of maintenance programs, including reactive, preventive and predictive maintenance. Preventive and predictive maintenance represent two proactive strategies by which companies can avoid equipment breakdowns. Weil (1998: 118–124) added another approach in his description of the maintenance continuum by including TPM (Total Productive Maintenance). TPM is an aggressive maintenance approach that seeks to improve equipment performance while continuing to avoid equipment failures (Swanson, 2001: 237–244). Finally we can add Reliability Centered Maintenance (RCM) to this notation.

Traditionally, many companies employed a *reactive* strategy for maintenance, fixing machines only when they stopped working. More recently, improved technology and the increased sophistication of maintenance personnel have led some companies to replace this type of reactive approach. A *proactive* strategy for maintenance utilizes preventive and predictive maintenance activities that prevent equipment failures from occurring. An *aggressive* strategy, like TPM, focuses on actually improving the function and design of the production equipment. While these newer maintenance strategies require greater commitments in terms of training, resources and integration, they are also expected to provide higher levels of equipment and plant performance (Swanson, 2001: 237–244).

A. Preventive Maintenance

Preventive maintenance (PM) can be defined as the activity undertaken regularly at pre-selected intervals while the device is satisfactorily operating to reduce or eliminate the accumulated deterioration; while repair is the activity to bring the device to a non-failed state after it has experienced a failure (Chen and Trivedi, 2002: 43-51). Mostly the cost occurred when a device fails is larger than the cost of PM, so it's worth carrying out PM.

The objectives of preventive maintenance programs are to reduce the incidence of breakdown or failure of equipment; extend useful life of production machinery; reduce total maintenance costs by substituting PM cost for repair cost; provide a safe working environment for employees; and improve product quality by keeping equipment in proper adjustment, well serviced and in good operating condition (Bateman, 1995: 19–21).

The basis for PM justification is that it is cheaper to repair or replace a component before it fails. The result of reactive maintenance, waiting until a machine needs repair to work on it, is that when a component fails, it is normally a catastrophic failure that carries with it collateral damage to other components. It is this collateral damage that increases the cost of reactive maintenance and is, therefore, an opportunity for savings by a preventive maintenance program (Bateman, 1995: 19–21).

Generally, there exist two types of PM schemes, i.e. condition-based and time-based preventive maintenance. For condition-based PM, the action taken after each inspection is dependent on the state of the system. It could be no action, or minimal maintenance to recover the system to the previous stage of degradation, or major maintenance to bring the system to as good as new state. For time-based PM, the preventive maintenance is carried out at predetermined time intervals to bring the system to as good as new state (Chen and Trivedi, 2002: 43-51). In this paper condition-based PM is used.

In condition-based maintenance, diagnostic equipment is used to measure the physical condition of equipment such as temperature, vibration, noise, lubrication and corrosion. When one of these indicators reaches a specified level, work is undertaken to restore the equipment to proper condition. This means that, equipment is taken out of service only when direct evidence exists that deterioration has taken place (Swanson, 2001: 237–244).

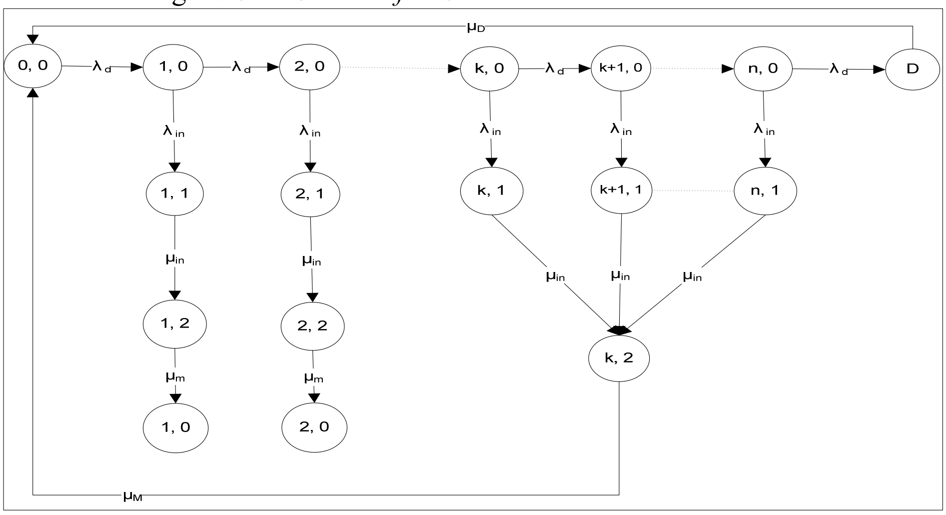
III. Model

The multi-stage exponential device deterioration failure model, which was introduced by Sim and Endrenyi (1988: 92–95), is used in the model. In this model, the system exposed to several stages of performance degradation and the time for the system to stay in each stage is assumed to be exponentially distributed (Chen and Trivedi, 2002: 43-51). If the deterioration left unattended, the process will lead to deterioration failure. Under deterioration failure, major PM is performed and the device is restored to 'as good as new' status (Sim and Endrenyi, 1993: 134–140).

For detecting the system's deteriorating status, the system undergoes periodical inspections. After each inspection, minimal PM, which is defined as the PM activity with limited effort and effect (Pham and Wang 1996: 425–438), may be carried out to restore the system to the starting deterioration stage.

The continuous time Markov Chain (CTMC) model with minimal and major PM is shown in Fig. 1.

Fig. 1: *CTMC model for Condition-Based Maintenance*



In the model, state (i, 0) represents the state in which the device is in the i^{th} deterioration stage but operational, state (i,1) represents the state in which the device is in i^{th} deterioration stage and under inspection, (i,2) is the state where the device is in i^{th} deterioration stage and is under maintenance, and state D is the deterioration failure state. The device is inspected after a random period that is exponentially distributed with mean $1/\lambda_{in}$. If the device failed, it is restored to state (0,0) (as good as new) with a mean repair time of $1/\mu_D$.

As we understand from Fig. 1, the deterioration stage is determined by inspection. The device is exposed to minimal maintenance if the deterioration stage is with $1 \leq i < k$, by which the device is restored to (i, 0). If the deterioration stage is with $k \leq i \leq n$, the device experiences major maintenance and restored to as good as new state (state (0, 0)). When the device is in deterioration failure state D, device is repaired to the state (0, 0).

From the above discussions, the notation in Fig. 1 is shown below:

n	total number of deterioration stages.
i	deterioration stage
k	major maintenance threshold
D	deterioration failure stage
$1/\lambda d$	mean time between failures
$1/\lambda_{in}$	mean time between inspections
$1/\mu_{in}$	mean duration of maintenance inspection
$1/\mu_D$	mean duration of repair
$1/\mu_m$	mean duration of minimal maintenance
$1/\mu_M$	mean duration of major maintenance

The proposed model can be used as a practical and systematic procedure for maintenance and reliability engineers. This model can be used for the systems whose condition can be deteriorated in time like elevators, manufacturing machines and etc.

IV. Analysis

The steady-state equations of the model:

$$\lambda_d P(0,0) = \mu_D P_D + \mu_M P(k,2) \quad (1)$$

$$[\lambda_d + \lambda_{in}]P(i,0) = \lambda_d P(i-1,0) + \mu_m P(i,2), \quad (2)$$
$$1 \le i < k$$

$$[\lambda_d + \lambda_{in}]P(i,0) = \lambda_d P(i-1,0), \quad (3)$$
$$k \le i \le n$$

$$\mu_{in} P(i,1) = \lambda_{in} P(i,0), \quad (4)$$
$$1 \le i \le n$$

$$\mu_m P(i,2) = \mu_{in} P(i,1), \quad (5)$$
$$1 \le i < k$$

$$\mu_M P(k,2) = \mu_{in} \sum_{i=k}^{n} P(i,1) \quad (6)$$

$$\mu_D P_D = \lambda_d P(n,0), \quad (7)$$

$$P(0,0) + P_D + \sum_{i=1}^{n} \sum_{j=0}^{2} P(i,j) = 1 \quad (8)$$

To solve the model, decomposition rules are used. After simplification, the following relationships between the state probabilities are found (the exact solution can be asked from the author):

1) P(k-1,0) = P(k-2,0) = … = P(1,0) = P(0,0)
2) P(k-1,1) = … = P(1,1) = $P(0,0)\dfrac{\lambda_{in}}{\mu_{in}}$
3) P(k-1,2) = … = P(1,2) = $P(0,0)\dfrac{\lambda_{in}}{\mu_m}$
4) P(n,0) = $P(0,0)\left(\dfrac{\lambda_d}{\lambda_d + \lambda_{in}}\right)^{n-k}$

5) $P_D = P(0,0)\dfrac{\lambda_d}{\mu_D}\left(\dfrac{\lambda_d}{\lambda_d + \lambda_{in}}\right)^{n-k}$

6) $P(i,1) = P(i,0)\dfrac{\lambda_{in}}{\mu_{in}}$, k ≤ i ≤ n

7)
$$P(k,2) = aP(0,0)\frac{\lambda_{in}}{\mu_M}\frac{1-a^{n-k}}{1-a}$$
$$a = \frac{\lambda_d}{\lambda_d + \lambda_{in}}$$

Define:

$$b \equiv \frac{\lambda_{in}}{\mu_m} \qquad c \equiv \frac{1-a^{n-k}}{1-a}$$
$$d \equiv \frac{\lambda_{in}}{\mu_{in}} \qquad e \equiv \frac{\lambda_d}{\mu_D}$$
$$f \equiv a^{n-k}$$

Because the sum of probabilities of all states is equivalent to one, we have:

$$P(0,0) = \frac{1}{k + (k-1)(b+d) + ac(1+b+d) + ef} \qquad \textbf{(9)}$$

V. Optimization

Optimizing maintenance and repair policies for system availability or total maintenance costs is the general purpose of the most researches. In this study, to evaluate the performance of the maintenance system, inspection interval is used. To find the optimal inspection interval, availability maximization and costs minimization procedures are used separately.

A. Availability maximization

When the optimization objective is to maximize the availability A, the optimal inspection interval could be found by:

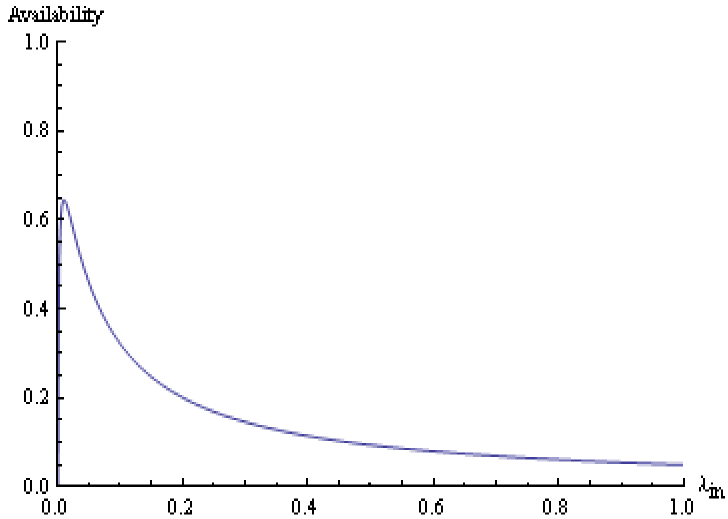
$\boldsymbol{A} = \boldsymbol{f} = P(0,0) + \sum_{i=1}^{n} P(i,0)$ and

$$\frac{df}{d\lambda_{in}} = 0.$$

For the optimization procedure we use the numerical values of n=7, k=4, λ_d=0.01, μ_{in}=0.2, μ_m=0.05, μ_M=0.01 and μ_d=0.005.

Then we get the solution of λ_{in} = 0.0109876 and the availability is %64.49. In other means to maximize the availability of the device, it should be inspected in every 91 minutes. In figure 2 the change of availability vs. λ_{in} is shown.

Fig. 2: *The Optimal λ_{in} For Different Λ To Maximize The Availability*



B. *Cost Minimization*

To evaluate the maintenance performance, cost minimization can also be used. The costs assigned in the model are given in Table 1.

Table 1: *System Operational Costs*

Cost	Meaning	Value
c_m	Cost of minimal maintenance	10
c_M	Cost of major maintenance	50
c_D	Cost of repair	100
c_1	Cost per unit time in down states due to maintenance	100
c_2	Cost per unit time in down states due to repair	100

The total maintenance cost is

$$C_s = \begin{aligned} & c_1\left(\sum_{i=1}^{n} P(i,1) + \sum_{i=1}^{k-1} P(i,2) + P(k,2)\right) + c_2 P_D \\ & + c_m \mu_m \sum_{i=1}^{k-1} P(i,2) \\ & + c_M \mu_M P(k,2) + c_D \mu_D P_D \end{aligned} \quad (10)$$

and the optimal inspection interval to minimize the maintenance cost can be found by solving the equation

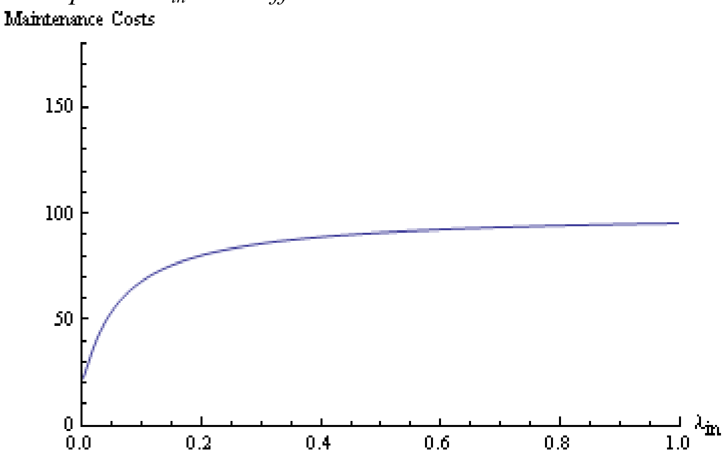
$$\frac{dC_s}{d\lambda_{in}} = 0$$

From the equation and using the same numerical values from the availability maximization procedure we found

$$\lambda_{in} = 0.000878$$

or in other way the system should be inspected in every 1138 minutes to minimize the cost. The total maintenance costs - λ_{in} graph is given in figure 3.

Fig. 3: *The Optimal Λ_{in} For Different Λ To Minimize The Maintenance Costs*



VI. Conclusion

In this paper, maintenance problem of a device which is under deterioration is examined. Due to the deterioration, the device's condition gets worse and a failure occurs inevitably. With the help of inspections, condition of the device should be known exactly. After the inspections, minimal or major preventive maintenance can be applied to improve availability of the device. A markov-chain based model is proposed for the device. To find the optimal inspection interval, decomposition rules are used. After the steady-state equations are proposed, a numerical example is given. Availability maximization and cost minimization are used to find the optimal inspection period.

From the given numerical values, it's seen that to maximize the availability, the device should be inspected in every 91 minute, whereas for cost minimization the optimal inspection period becomes 1138 minute.

References

Ben-Daya, M., Duffuaa S.O. and Raouf A. (2000), Maintenance, Modeling and Optimization, Kluwer Academic Publishers, Ma., USA.

Ben-Daya M. and Duffuaa S.O. (1995), "Maintenance and Quality: The Missing Link", *Journal of Quality in Maintenance Engineering*, 1 (1), p. 20 26.

Dervitsiotis K.N. (1981), Operations Management, McGraw-Hill International Book Co., Japan.

Duffuaa S.O. and Al-Sultan K.S. (1997), "Mathematical Programming Approaches for the Management of Maintenance Planning and Scheduling", *Journal of Quality in Maintenance Engineering*, 3 (3), p. 163 176.

Swanson L. (2001), "Linking Maintenance Strategies to Performance", *International Journal of Production Economics*, 70, p. 237 244.

Bateman J.F. (1995), "Preventive maintenance: Stand Alone Manufacturing Compared with Cellular Manufacturing", *Industrial Management*, 37 (1), p. 19 21.

Weil, N.A. (1998), "Make the Most of Maintenance", *Manufacturing Engineering*, 120 (5), p. 118 124.

Chen D. and Trivedi K.S. (2002), "Closed-Form Analytical Results for Condition-Based Maintenance", *Reliability Engineering and System Safety*, 76, p. 43 51.

Sim S.H and Endrenyi J. (1988), "Optimal Preventive Maintenance with Repair", IEEE *Transactions on Reliability*, 37 (1), p. 92 95.

Sim S.H. and Endrenyi J. (1993), "A Failure-Repair Model with Minimal & Major Maintenance", *IEEE Transactions on Reliability*, 42 (1), p. 134 140.

Pham H. and Wang H. (1996), "Imperfect Maintenance", *European Journal of Operational Research*, 94 (3), p. 425 438.