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A Survey of Preventive Maintenance Planning Models, Techniques and Policies for an Ageing and Deteriorating Production Systems

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Abstract

In the past many decades, breakdown, maintenance and replacement issues of deteriorating machines and systems are extensively studied within the literature. A number of maintenance and replacement models, techniques and policies are created, documented and tested. However, of these models are comprised of some classes

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of maintenance policies, such as age replacement and random age replacement policies, policy of replacing blocks, policy of periodic preventive maintenance, failure limit policy, sequential preventive maintenance policy, repair value limit policy, policies for repair deadline and repair range investigations, reference time policy, mixed age policy, preparation maintenance policy, cluster maintenance policy, expedient maintenance policy, etc. All policies have completely different characteristics, benefits and limitations. This survey summarizes, classifies, and compares varied existing maintenance policies for each single and multiple-unit systems. The stress of our study is on single unit systems.

Keywords

Survey, Maintenance Policy, Maintenance, Reliability, Replacement, Optimization, Deteriorating Systems, Production Systems.

Introduction

In the past many decades, breakdown, maintenance and replacement issues of deteriorating machines and systems are extensively studied within the literature. A number of maintenance and replacement models, techniques and policies are created, documented and tested. However, of these models are comprised of some classes of maintenance policies, such as age replacement and random age replacement policies, policy of replacing blocks, policy of periodic preventive maintenance, failure limit policy, sequential preventive maintenance policy, repair value limit policy, policies for repair deadline and repair range investigations, reference time policy, mixed age policy, preparation maintenance policy, cluster maintenance policy, expedient maintenance policy, etc. All policies have completely different characteristics, benefits and limitations. This survey summarizes various existing maintenance policies for each single and multiple-unit system. The stress of our study is on single unit systems.

In order to meet both Preventive and Corrective Maintenance of a production system, it is required to allocate the repair resources properly along with good planning and maintenance scheduling. It's studied and all accepted that the effectiveness of a system depends on quality of its design additionally with the regular maintenance actions because the proper maintenance actions are required to forestall it from breakdown. In fact, the maintenance policies that are selected from an economic point of view create a manageable approach in

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reliability theory. In this article, we have discussed the maintenance policies associated with single and multi-unit systems.

Summary of Existing Literature

The Preventive Maintenance Planning Models, Techniques and Policies have been extensively studied, experimented and documented in the past. Barlow and Hunter (1960) [1], Nakagawa (1979) [2], Singh (1989) [3] have computed the state probabilities of a complex production system in their research articles. Zhao (1994) [4] have developed a generalized availability model in their research for repairable components within a production system. In a research by Edward A. Silver et al. (1995) [5], a preventive maintenance with limited historical data is presented. In a research by Russell D. Meller et al. (1996) [6], results of preventive maintenance on overall system cost and its buffer size is discussed. Zhang (1996) [7] have studied the stochastic behaviour of an (N+1) unit stand by production system. M.A.J. Smith et al. (1997) [8] in their article have discussed the uptime, downtime and costs associated in the preventive maintenance of 1 out of n systems. I. Gertsbakh et al. (1997) [9] in their article have discussed a selection for the most suitable time scale for preventive maintenance in diverse environments. In a research by K.K. Lai et al. (2000) [10] a case study on practices of preventive maintenance and replacement for engines is presented. In a research by D. Gupta et al. (2001) [11], defines the relationship between preventive maintenance and manufacturing system performance. In a research by Ruey Huei Yeh et al. (2001) [12] an optimal Preventive maintenance warranty policy for repairable products is presented. In a research by Sophie Bloch-Mercier et al. (2002) [13] have presented a preventive maintenance policy with consecutive monitoring procedure for a Markov deteriorating system. In a research by Hongzhou Wang (2002) [14] a survey of maintenance policies of deteriorating systems is presented. Grail et al (2002) [15] presented a preventive maintenance technique for a gradually deteriorating single unit production systems. In a research by Muh-Guey Juang et al. (2004) [16] a Bayesian method on adaptive preventive maintenance problem is presented. In a research by Timothy S. Vaughan, (2005) [17] on failure replacement and preventive maintenance spare parts ordering policy is presented. In a research by N. Sortrakul et al. (2005) [18] have presented the use of Genetic algorithms in an integrated single-machine preventive maintenance planning and production scheduling. In a research by J. Jaturonnatee et al. (2006) [19] an optimal preventive maintenance through corrective minimal repair of leased equipments have been discussed. Mohanta et al. (2006) [20] have presented an intelligent computational method for preventive maintenance of a captive thermal plant. Todinav (2007) [21] have presented a new method for optimizing the topology of engineering production systems based on reliability allocation based on cost. Kumar et al (1991) [22], Garg and Singh (2005) [23], Singh (2007) [24] and similarly some other writers also have applied reliability technologies to various Industrial and production systems to obtain good results. In a research by E.H. Aghezzaf et al. (2007) [25] integrated production and preventive maintenance planning model is presented. In a research by Yeh Lam, (2007) [26] a geometric process maintenance model with preventive repair is presented. In a research by El-Houssaine Aghezzaf et al. (2008) [27] have presented an integrated production planning and preventive maintenance technique for deteriorating production systems. In a research by Seong-Jong Joo (2009) [28] a dynamic approach of scheduling preventive maintenance for modular designed components is presented. In a research by Chin-Tai Chen, (2011) [29] a dynamic preventive maintenance strategy for a multi-state aging and deteriorating production system is presented. In a research by Ruey Huei Yeh et al. (2011) [30] a preventive-maintenance policy for leased products considering all aspects of applicable maintenance costs is discussed. In a research by Chung-Ho Wang et al. (2011) [31] have discussed a technique to minimize series-parallel system's periodic preventive maintenance cost using improved particle swarm optimization. In a research by Julien Rabatel et al. (2011) [32] have presented a detection of anomaly point in sensor monitoring data for preventive maintenance.

Review of Preventive Maintenance Models/Methods for Deteriorating Systems

Maintenance can broadly be classified into two major categories: corrective and preventive maintenance. Corrective maintenance or CM is type maintenance where a maintenance activity takes place only when there is a system failure. This can also be referred as a repair process. CM means all maintenance actions performed as a result of system failure, to restore it to an operational condition. Replacement of faulty parts or components is a perfect type of maintenance.

Preventive maintenance or PM is a type of maintenance that occurs when a system is in operating condition by providing systematic inspection and detection of parts for system's prevention or protection from failures.

In this review, we have used the term maintenance in a general way to represent both preventive and corrective maintenance. This survey summarizes various

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existing preventive maintenance methods and models.

Preventive Maintenance Models and Methods

PM Model to Calculate Approximate Numbers of Optimal Maintenance Inspections [33, 35, 36]

This model can be used to obtain the optimum number of inspections per facility per unit of time. Total facility downtime is defined by the equation 1.

$$Downtime_{total} = nT_i + \frac{CT_f}{n} \tag{1}$$

where,
$Downtime_{total}$ = Total Downtime for a facility/system (per unit of time),
c = constant associated with a particular system/facility,
T_f = facility downtime because of breakdown/failure,
T_i = facility downtime because of inspection,
n = number of inspections per facility per unit time.

By differentiating equation 1 with respect to n, we get:

$$\frac{dDowntime_{total}}{dn} = T_i - \frac{c * T_f}{n^2} \tag{2}$$

By setting equation 2 equals to zero, we gets:

$$n^* = \left(\frac{c * T_f}{T_i}\right)^{1/2} \tag{3}$$

where,
n^* = Optimum number of inspections per facility per unit of time.
By substituting equation 3 into equation 1, we gets:

$$Downtime^*_{total} = 2\left(c * T_i T_f\right)^{1/2} \tag{4}$$

where,
$Downtime_{total}$ = Total Optimal Downtime for a system/facility (per unit of time).

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PM Model based on Reliability and MTTF Calculation [33, 37, 38, 39, 40]

A mathematical model which can be used to calculate the reliability and MTTF (Mean Time to Failure) of a system which is under periodic maintenance. The following assumptions are made for this PM Model:

1. A failed part of the system/equipment is replaced with a new similar part,
2. A routine Periodic maintenance (PM) is performed on the system after every h hours, since its installation.

The reliability of a system can be calculated using equations 5 - 8, similarly the MTTF of a system can be calculated using equations 9 - 11 depending upon the configuration of the system.

In a case, where n number of units forms a series system and if any one of such units fails, the entire system fails. All blocks of the system must work normally for successful operation of the entire system. Reliability ($R_A(h)$) of a single unit A, at time h, for A = 1,2,3,...,n. can be expressed as:

$$R_A(h) = e^{-\lambda_A h} \tag{5}$$

where, λ_A = Constant failure rate (failures per hour) of a single unit A, for A = 1,2,3,...,n.

Overall series system's reliability ($R_S(h)$) at time h (with non-identical serial units) can be expressed as:

$$R_S(h) = e^{-\sum_{A=1}^{n} \lambda_A h} \tag{6}$$

In this case, where n number of simultaneously working units forms a parallel system and at least one of the units must work normally successful operation of the entire system. Overall parallel system's reliability $R_{PS}(h)$ at time h (with non-identical parallel units) can be expressed as:

$$R_{PS}(h) = 1 - \prod_{A=1}^{n} (1 - e^{-\lambda_A h}) \tag{7}$$

Overall parallel system's reliability $R_{PS}(h)$ at time h (with identical parallel units) can be expressed as:

$$R_{PS}(h) = 1 - (1 - e^{-\lambda h})^n \tag{8}$$

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Series system's MTTF (Mean Time to Failure) can be calculated as:

$$MTTF_S = \sum_{A=1}^{n} \lambda_A \tag{9}$$

Parallel system's MTTF (Mean Time to Failure) can be calculated as:

$$MTTF_{PS} = \frac{1}{\lambda} \sum_{A=1}^{n} \frac{1}{A} \tag{10}$$

The system's MTTF (Mean Time to Failure) for a system under Preventive Maintenance is given by:

$$MTTF_{PM} = \frac{\int_0^H R(T)dt}{1 - R(H)} \tag{11}$$

where, $R(H)$ is the reliability of a redundant system, undergoing preventive maintenance after every H hours, $R(T)$ is the reliability of the system to operate H hours after installation/preventive maintenance/replacement of the part.

PM Model to Minimize System's/Equipment's/Facility's Downtime [33, 36, 41, 42, 43]

Total Downtime for a System/Equipment/Facility can be defined as:

$$downtime_{total}(f) = downtime_{repair} + downtime_{inspection} \tag{12}$$

$$downtime_{total}(f) = \frac{\lambda(f)}{\mu_f} + \frac{f}{\theta} \tag{13}$$

where,
$downtime_{total}(f)$ = Total downtime for a System/Equipment/Facility per unit of time,
$downtime_{repair}$ = downtime due to repair for a System/Equipment/Facility per unit of time,
$downtime_{inspection}$ = downtime due to inspection for a System/Equipment/Facility per unit of time,
f = inspection frequency,
$\lambda(f)$ = System/Equipment/Facility failure rate,
μ_f = System/Equipment/Facility repair rate,
$\frac{1}{\theta}$ = mean of inspection times which is exponentially distributed.

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Now, after differentiating equation 13 with respect to f, we get:

$$\frac{d}{df} downtime_{total}(f) = \frac{d\lambda(f)}{df \mu_f} + \frac{1}{\theta} \tag{14}$$

setting equation 14 equals to zero, we gets:

$$\frac{d\lambda(f)}{df} = -\frac{\mu_f}{\theta} \tag{15}$$

The inspection frequency (f) would be optimum when the left and right sides of the equation 15 becomes equal. At this point we will get the minimal downtime from a system/equipment/facility.

PM Model to Optimize the Frequency of Inspections [33, 36, 41, 42, 43]

This PM Model can be utilized to calculate the optimum number of inspections to be carried out at the System/Equipment/Facility to minimize the cost and losses in production due to the preventive maintenance. The following assumptions are associated with this PM Model:

1. The System/Equipment/Facility failure rate is a function of inspections,
2. Inspection time is exponentially distributed,
3. System/Equipment/Facility failure and repair rates are constant.

For a System/Equipment/Facility, Profit Rate (PR) per unit of time can be calculated as:

$$PR = p_{ndt} - L_{ins} - L_{repair} - C_{ins} - C_{repair} \tag{16}$$

where, p_{ndt} = profit at zero downtime (no downtime) losses,
L_{ins} = production loss per unit of time due to inspection,
L_{repair} = production loss per unit of time due to repair,
C_{ins} = cost of inspection per unit of time,
C_{repair} = cost of repair per unit of time.

Rewriting equation 16 as:

$$PR = p_{ndt} - \frac{p_{ndt} f}{\theta} - \frac{p\lambda(f)}{\mu} - \frac{AC_{ins}}{\theta} - \frac{AC_{repair}\lambda(f)}{\mu} \tag{17}$$

where, f = inspection frequency per unit of time,
$\frac{1}{\theta}$ = mean of inspection times which is exponentially distributed,
p_{ndt} = profit at zero downtime (no downtime) losses,
AC_{ins} = average cost of inspection,
AC_{repair} = average cost of repair,
λ = system's/equipment's failure rate,
μ = system's/equipment's repair rate.

Now, after differentiating equation 17 with respect to f, then equating it equals to zero and then rearranging it, gets:

$$\frac{d\lambda(f)}{df} = \frac{-\left[\frac{1}{\theta}(p_{ndt} + AC_{ins})\right]}{\left(\frac{p_{ndt}}{\mu} + \frac{AC_{repair}}{\mu}\right)} \tag{18}$$

The inspection frequency f would be optimal when both left and right sides of the equation 18 becomes equal. At this point we will get the maximum value of profit from a system/equipment/facility.

Preventive Maintenance Markov Model [33, 36, 42, 43, 44]

Markov Model for Preventive Maintenance represents a system/equipment/facility that can either fails completely or undergoes a routine preventive maintenance after every specific period of time [33, 36, 42, 43, 44] as shown in figure 1. This

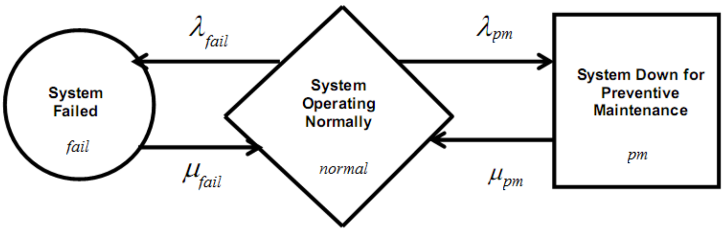

Figure 1: *State Transition Diagrams for the PM Markov Model [33, 36, 42, 43, 44, 45]*

PM Model helps to predict the system's probabilities for its availability, down for its maintenance, down due to failure. The following assumptions are made for this PM Model:

1. System have a constant preventive maintenance, repair and failure rates,

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2. System become well functional just after its repair or preventive maintenance.

The equation 19 shows the Markov Method for figure 1.

$$\frac{dP_{normal}(t)}{dt} + (\lambda_{fail} + \lambda_{pm}) = \mu_{fail} P_{fail}(t) + \mu_{pm} P_{pm}(t) \tag{19}$$

$$\frac{dP_{pm}(t)}{dt} + \mu_{pm} P_{pm}(t) = \lambda_{pm} P_{normal}(t) \tag{20}$$

$$\frac{dP_{fail}(t)}{dt} + \mu_{fail} P_{fail}(t) = \lambda_{fail} P_{normal}(t) \tag{21}$$

where, S = state of the system/equipment, for $S = normal$ (system is operating normally), $S = fail$ (system failure), $S = pm$ (system is down due to preventive maintenance).
$P_S(t)$ = Probability of a system/equipment to be in S^{th} state at time t, for $S = normal, fail, pm$
λ_{fail} = failure rate of a system/equipment
μ_{fail} = repair rate of a system/equipment
λ_{pm} = rate of a system/equipment down for preventive maintenance
μ_{pm} = rate of a system/equipment preventive maintenance performance
Av = rate of availability for system/equipment

Solving equations 19, 20 and 21, at $t = 0$, keeping $P_{normal}(0) = 1$ and $P_{pm}(0) = P_{fail}(0) = 0$, we gets:

$$P_{normal}(t) = \frac{\mu_{pm}\mu_{fail}}{c_1 c_2} + \left[\frac{(c_1 + \mu_{pm})(c_1 + \mu_{fail})}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(c_2 + \mu_{pm})(c_2 + \mu_{fail})}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{22}$$

$$P_{fail}(t) = \frac{\lambda_{fail}\mu_{pm}}{c_1 c_2} + \left[\frac{\lambda_{fail} c_1 + \lambda_{fail}\mu_{pm}}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu_{pm} + c_2)\lambda_{fail}}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{23}$$

$$P_{pm}(t) = \frac{\lambda_{pm}\mu_{fail}}{c_1 c_2} + \left[\frac{\lambda_{pm} c_1 + \lambda_{pm}\mu_{fail}}{c_1(c_1 - c_2)}\right] e^{c_1 t} - \left[\frac{(\mu_{fail} + c_2)\lambda_{pm}}{c_2(c_1 - c_2)}\right] e^{c_2 t} \tag{24}$$

where,

$$c_1, c_2 = \frac{-Av \pm [Av^2 - 4(\mu_{pm}\mu_{fail} + \lambda_{fail}\mu_{pm} + \lambda_{pm}\mu_{fail})]^{1/2}}{2} \tag{25}$$

$$Av \equiv (\mu_{fail} + \mu_{pm} + \lambda_{fail} + \lambda_{pm}) \tag{26}$$

$$c_1 + c_2 = -Av \tag{27}$$

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$$c_1c_2 = (\mu_{pm}\mu_{fail} + \lambda_{pm}\mu_{fail} + \lambda_{fail}\mu_{pm}) \tag{28}$$

When, time t becomes very large, the steady state probabilities of system/equipment would become:

$$P_{normal} = \frac{\mu_{fail}\mu_{pm}}{c_1c_2} \tag{29}$$

$$P_{pm} = \frac{\lambda_{pm}\mu_{fail}}{c_1c_2} \tag{30}$$

$$P_{fail} = \frac{\lambda_{fail}\mu_{pm}}{c_1c_2} \tag{31}$$

where, P_{normal} = steady state probability of a system/equipment to work normally (steady state availability), P_{pm} = steady state probability of a system/equipment down due to preventive maintenance, P_{fail} = steady state probability of a system/equipment failure.

PM Model to Minimize its Total Cost Subject to Achieve a Fixed Reliability [46, 47]

In this PM model, attempts are made to minimize the total cost of the preventive maintenance subject to the constraint that a minimum level of system reliability should be achieved, assuming that the equipments are arranged in series making it a series-system.

The system reliability for a series-system can be defined as:

$$R_{series} = \prod_{i=1}^{N}\prod_{p=1}^{T} e^{-E[N_{ip}]} \tag{32}$$

$$R_{series} = \prod_{i=1}^{N}\prod_{p=1}^{T} e^{-\left[\lambda_i\left((A'_{i,p})^{\beta_i} - (A_{i,p})^{\beta_i}\right)\right]} \tag{33}$$

where, i is the component from 1 to N, and p is the period of time from 1 to T.

The PM model that minimize its total cost subject to achieve a fixed reliability can be expressed as:

$$TotalCost_{minimum} = \sum_{i=1}^{N}\sum_{p=1}^{T}\left[FC_i * \lambda_i * \left((A'_{i,p})^{\beta_i} - (A_{i,p})^{\beta_i}\right) + M_i * m_{i,p} + R_i * r_{i,p}\right]$$

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$$+\sum_{p=1}^{T}\left[Z\left(1-\prod_{i=1}^{N}(1-(m_{i,p}+r_{i,p}))\right)\right] \tag{34}$$

subject to:
$A_{i,1} = 0$ (for $i = 1, ..., N$, i.e. at $p = 1$, starting of time period, age of component i is zero)

$\prod_{i=1}^{N}\prod_{p=1}^{T} e^{-\left[\lambda_i\left((A'_{i,p})^{\beta_i}-(A_{i,p})^{\beta_i}\right)\right]} \geq R_{series}$ (i.e. a minimum level of system reliability should be achieved)

$r_{i,p} + m_{i,p} \leq 1$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A_{i,p}$, $A'_{i,p} \geq 0$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A_{i,p} = (1 - m_{i,p-1})(1 - r_{i,p-1})A'_{i,p-1} + m_{i,p-1}(\alpha * A'_{i,p-1})$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A'_{i,p-1} = A_{i,p-1} + \frac{T}{p}$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

where,
FC_i = cost of each failure for a component i
λ_i = failure rate for a component i
$A_{i,p}$ = age of component i at the end of period p
M_i = maintenance cost performed on component i during period p
$m_{i,p}$ = binary variable of maintenance action for component i at period p ($m_{i,p} = 1$, if the component i is maintained at period j; otherwise $m_{i,p} = 0$)
R_i = replacement cost or the initial purchasing cost of the component i
$r_{i,p}$ = binary variable of replacement action for component i at period p ($r_{i,p} = 1$, if the component i is replaced at period j; otherwise $r_{i,p} = 0$)
Z = fixed cost for downtime for a period p

The function shown in equation above computes the total cost as a simple addition of various costs involved in each period of time for a system downtime based on maintenance/repair cost and the cost towards the expected number of failures. A more accurate economic calculations of these costs is also possible by considering applicable interest rates, inflation rates in our calculation for future costs towards maintenance.

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PM Model to Maximize the Reliability of a System/Equipment Subject to a Fixed Limit of budget/Cost for Maintenance [46, 47]

The objective of this PM model is to achieve the maximum system's/equipment's reliability, through the choices of maintenance and replacement actions and to stay within the planned budget/cost for the PM activities.

$$Reliability_{maximum} = \prod_{i=1}^{N}\prod_{p=1}^{T} e^{-\left[\lambda_i\left((A'_{i,p})^{\beta_i}-(A_{i,p})^{\beta_i}\right)\right]} \tag{35}$$

`subject to:`
$A_{i,1} = 0$ (for $i = 1, ..., N$, i.e. at $p = 1$, starting of time period, age of component i is zero)

$\sum_{i=1}^{N}\sum_{p=1}^{T}\left[FC_i * \lambda_i * \left((A'_{i,p})^{\beta_i} - (A_{i,p})^{\beta_i}\right) + M_i * m_{i,p} + R_i * r_{i,p}\right]$
$+\sum_{p=1}^{T}\left[Z\left(1-\prod_{i=1}^{N}(1-(m_{i,p}+r_{i,p}))\right)\right] \leq Budget_{total}$ (i.e. to stay within the planned budget/cost for the PM activities)

$r_{i,p} + m_{i,p} \leq 1$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A_{i,p}$, $A'_{i,p} \geq 0$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A_{i,p} = (1 - m_{i,p-1})(1 - r_{i,p-1})A'_{i,p-1} + m_{i,p-1}(\alpha * A'_{i,p-1})$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

$A'_{i,p-1} = A_{i,p-1} + \frac{T}{p}$ (for $i = 1, ..., N$ and $p = 1, ..., T$)

`where,`
FC_i = cost of each failure for a component i
λ_i = failure rate for a component i
$A_{i,p}$ = age of component i at the end of period p
M_i = maintenance cost performed on component i during period p
$m_{i,p}$ = binary variable of maintenance action for component i at period p ($m_{i,p} = 1$, if the component i is maintained at period j; otherwise $m_{i,p} = 0$)
R_i = replacement cost or the initial purchasing cost of the component i
$r_{i,p}$ = binary variable of replacement action for component i at period p ($r_{i,p} = 1$, if the component i is replaced at period j; otherwise $r_{i,p} = 0$)
Z = fixed cost for downtime for a period p

Conclusion and Future work

The motivation of this study was to summarize the preventive maintenance methods and models that are existing in the previous research work published by various researchers. This research was limited to the numbers of research articles, project reports, case-studies we managed to access using internet. We have presented about seven models and methods in this article which can be further implemented/tested on a industrial/production system to check the effectiveness of their ongoing preventive maintenance schedules and plans.

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