Asian Review of Mechanical Engineering
ISSN: 2249-6289 (P) Vol.1 No.1, 2012, pp.13-24
© The Research Publication, www.trp.org.in
DOI: https://doi.org/10.51983/arme-2012.1.1.2510

Maintenance Policies of Single and Multi-Unit Systems in the Past and Present

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(Received on 01 December 2011 and accpeted on 05 March 2012)

***Abstract*-This paper surveys the literature related to maintenance policies for single and multi-unit systems. The emphasis is on work appearing in different periods. The literature is divided into two main categories single and multi unit system. The single unit system is divided into six sub-categories like: Age-dependent, Periodic, Failure limit policy, Sequential, Repair limit, Repair number counting and reference time policy. Similarly policies of multi-unit are divided into two sub-categories;viz Group and Opportunistic maintenance policies; Each kind of policy has different characteristics, advantages and disadvantages with lot of contributions from Research scientist and Technologists. Around 150 authors and their research works are presented in the reference section. It will help the reader to select the exact policy for their organization and the reference section will be helpful for further study and further knowledge about different existing maintenance practices.**

Keywords: **Maintenance, Risk Based Maintenance, Failure, Preventive Maintenance, Operation**

I. INTRODUCTION

In this Paper the maintenance policies related to single-unit or multi-unit systems are discussed. The preventive maintenance system had been studied by several authors in the past. Barlow and Hunter(1960),N akagawa (1979), Singh(1989), computed the state probabilities of a complex system. Zhao (1994), developed a generalized availability model for repairable component. Zhang 1996, studied the stochastic behavior of an (N+1) unit stand by system. Grail *et al* (2002) presented a P.M. structure for a gradually deteriorating single unit system. Mohanta *et al.* (2006) describes the intelligent maintenance scheduling of a captive thermal plant using intelligence computational techniques. Todinav (2007) proposed a new method for optimization of the topology of engineering systems based on reliability allocation by maximizing the total cost. Kumar *et al* (1991) Garg and Singh (2005), Singh (2007) and some other writers applied reliability technologies to various Industrial systems obtaining important results. Proper maintenance planning and scheduling of the production systems is required to allocate the repair resources to meet both P.M and C.M.

A wide and recent study of preventive maintenance models can be found. The classical age and block replacement policies are useful for failures that are detected as soon as they occur (revealed failures); In this situation repairs can be immediately initiated. The opposite case corresponds to unrevealed failures, that is, those, which remain undiscovered unless some kind of inspection or testing is carried out. This usually happens in stored equipment, standby units.

Badı *et al.* analyzed the existence of a cost optimizing policy within the context of an inspection model which involves corrective maintenance whenever a failure is detected, and having no effect in the unit reliability. In Ref. [14] a preventive maintenance procedure is considered where inspections and maintenance actions take place at different times. Maintenance policies that can be used under unrevealed failures are found in Refs. [16-17,18]. Hong-Fwu Yu *et al.* Presented A mixed inspection policy for CSP-2 and precise inspection under inspection errors and return cost. Jui-Hsiang Chiang proposed a control limit maintenance policy such that the system is inspected at T, 2T, .. to identify system state and then an action from (do-nothing, repair, replacement) is taken. The optimal mixed inspection policy is determined by using the criterion of maximizing the unit net profit. For a continuous-time multi-state Markovian deteriorating (production) system subject to aging and fatal shocks and with states 0 (perfect state) <1<2< …<L (complete failure), Chun-Yuan Cheng showd that the incorporation of the Total Productive Maintenance (TPM) into the manufacturing machine is a success in that: the decrease of the machine failure rate and the improvement of the machine   reliability. Ming-Yuh Chen investigated preventive-maintenance warranty (PMW) policies for repairable products with age-dependent maintenance costs. The primary role of warranty is to offer post-sale remedy for consumers when a product fails to fulfill its intended performance during a warranty period. Eliminating costly unscheduled shutdown maintenances and accordingly reducing the failures of production systems as a whole help deliver the promises on ordered products. Muhammed Ucar stressed the need for more efficient maintenance and service strategies, the approaches of condition-based proactive maintenance, collaborative maintenance, remote maintenance and service support, provision for real-time information access, and integration of production with maintenance have evolved into a new phenomenon called e-maintenance to meet the needs of the future e-automation manufacturing world.

Barlow and Proshan (1965, 1975), Van Der Duyn Schouten (1996) and Dekker et al. (1997) surveyed and summarized the research and practice in maintenance area . This survey is organized into two sections reflecting maintenance policies of single-unit systems and multi-unit systems. Dekker (1996), Pham and Wang (1996), Dekker *et al.* (1997) and Jensen (1995) surveyed and summarize the research and practices in the maintenance area. In the survey, a classification scheme of maintenance models is presented. The idea is to classify maintenance models such that a decision maker can recognize the model that best fits his maintenance problem. Hundreds of maintenance models fall into the age replacement policy and the failure limit policy. Therefore, this review, surveys existing maintenance models in terms of maintenance policies that they belong to. This survey is organized into two sections, maintenance policies of single-unit systems and multi-unit systems. Since maintenance policies for single-unit systems are more established, and are the basis for maintenance policies of multi-unit systems, this work is more focused on single-unit systems. Figure 1 shows the overview of maintenance approaches in the Industry and figure 2 characteristics of each kind of maintenance policy.

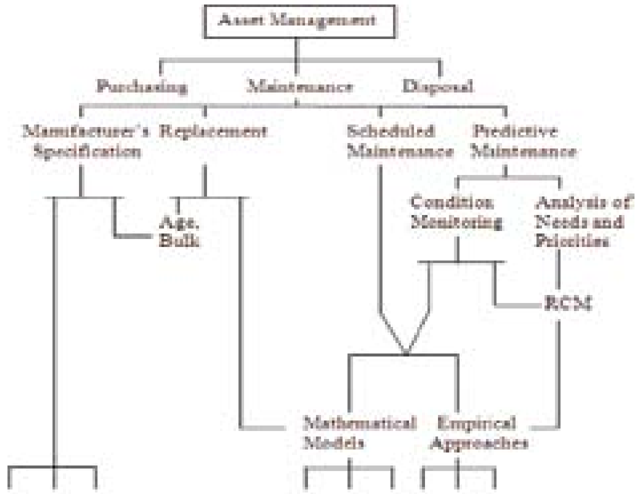


Fig. 1 Overview of maintenance approaches

II. STRATEGY AND TERMINOLOGY

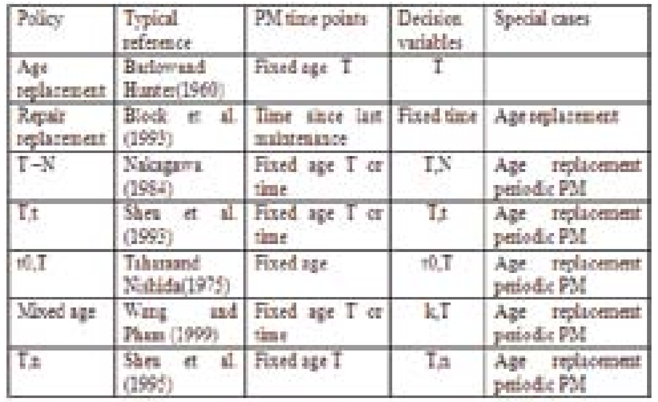
Presenting a scientific review on a certain topic implies that one tries to discuss all relevant articles. The search engines used here are google scholar, scirus and scopus, and (online) database, science direct, jstor and mathscinet. It is primarily searched on key words, abstracts and titles, but also searched within the papers for relevant references. Papers published in books or proceedings that are not electronically available are likely to have escaped terminology is another important issue. As the use of other terms can hide a very interesting paper, the edition has been delineated by maintenance, replacement or inspection on one hand and optimization on the other hand. The vast literature on maintenance of single and multi-component systems has been reviewed earlier by others. Therefore, it is also consulted existing reviews and overview articles in this edition. moreover, it has been applied a citation search (looking both backwards in time and forwards in time for citations) to all articles found. this citation search is an indirect search method, whereas the above methods are direct methods. the advantage of this method is that one can easily distinguish clusters of related articles.

III. MAINTENANCE POLICIES OF ONE-UNIT SYSTEMS

As mentioned earlier, the maintenance models are classified into different kinds of maintenance policies. this section summarizes, classifies, and compares maintenance policies of one-unit systems. The first five subsections discuss the maintenance policies with PMs and another subsection without preventive maintenance and the next three on maintenance of multi unit system. The last subsection provides a summary. The basic assumptions for single-unit systems are that the unit lifetime has increasing failure rate (IFR).

A. Age-Dependent PM Policy: The most common and popular maintenance policy might be the age-dependent pm policy. Under this policy, a unit is always replaced at its age t or failure, whichever occurs first, where t is a constant (Barlow and Hunter, 1960) if t is a random variable, the policy is the random age-dependent maintenance policy. details of age replacement policy can be found in Valdez-flores and Feldman (1989) and pham and wang (1996). Tahara and Nishida (1975) introduced a maintenance policy which state that ‘‘replace the unit when the first failure after t0 hours of operation or when the total operating time reaches t (0≤ t0 ≤ t) whichever occurs first; failures in (0, t0) are removed by minimal repair’’; if t0 = 0, it becomes the age replacement policy, and if t0 = t it will be periodic replacement with minimal repair at failure policy. Nakagawa (1984) extends the age replacement policy to replacing a unit at time t or at n number of failures, whichever occurs first, and undergoes minimal repair at failure between replacements. The decision variables for this policy are t and n; if $n = 1$, this policy is age replacement policy or is called t –n policy. Wang and Pham (1999) make another extension which is called ‘‘mixed age pm policy’’. in this policy, after n th imperfect repair, there are two types of failures; type 1 failure might be total breakdowns, another type 2 failure is as a slight and easily fixed problem. When a failure occurs, it is a type 1 failure with probability $p(t)$ and a type 2 failure with probability $q(t) = 1 - p(t)$. After the first n imperfect repairs, the unit will be subject to a perfect maintenance at age t or at the first type 1 failure. The policy decision variables are t and n; if $p(t) = 0$ and $n=0$ it becomes periodic replacement with minimal repair at failure policy; if $p(t) = 1$ and $n = 0$, it is age replacement policy. studies on the age-dependent pm policy are made by morse (1958). Various age-dependent pm policies are summarized and listed in Table I.

Table 1 Summary of age-dependent PM policies



Policy	Typical reference	PM time points	Decision variables	Special cases
Age replacement	Barlowand Hunter(1960)	Fixed age T	T	
Repair replacement	Block et al. (1993)	Time since last maintenance	Fixed time	Age replacement
T –N	Nakagawa (1984)	Fixed age T or time	T,N	Age replacement periodic PM
T,t	Sheu et al. (1993)	Fixed age T or time	T,t	Age replacement periodic PM
t0,T	Taharaand Nishida(1975)	Fixed age	t0,T	Age replacement periodic PM
Mixed age	Wang and Pham (1999)	Fixed age T or time	k,T	Age replacement periodic PM
T,n	Sheu et al. (1995)	Fixed age T	T,n	Age replacement periodic PM

B. Periodic PM Policy

In the periodic PM policy, a unit is preventively maintained upto fixed time intervals kT ($k = 1, 2$--) independent of the failure history and repaired at intervening failures T where T is a constant. Another policy in this class is ‘‘periodic replacement with minimal repair at failures’’ policy under which a unit is replaced at predetermined times kT ($k = 1, 2$----) and failures are removed by minimal repair (Barlow and Hunter, 1960). One expansion of the ‘‘periodic replacement with minimal repair at failure’’ policy is the one where a unit receives imperfect PM every T time unit, and it is replaced after its age has reached $(O+1)T$ time units, where O is the number of imperfect PMs (Liu *et al.,* 1995). The policy decision variables are O and T; if $O = 0$, this policy is ‘‘periodic replacement with minimal repair at failure’’ policy. Berg and Epstein (1976), have modified the policy by setting an age limit. Under this policy, a failed unit is replaced by a new one; however, units whose ages are less than or equal to $t0$ ($0 \leq t0 \leq T$) at the scheduled replacement times kT ($k = 1,2$---) are not replaced, but remain working until failure or the next replacement time point. Obviously, if $t0 = T$, it reduces to the block replacement policy. Tango (1978) suggests that some failed units be replaced by used ones, which have been collected before the scheduled replacement times. Under this extended block replacement policy, units are replaced by new ones at periodic times kT, ($k = 1,2$---) The failed units are, however, replaced by either new ones or used ones based on their individual ages at the times of failures. A time limit r is set in this policy, similar to $t0$ as remarked by Berg and Epstein (1976). If a failed unit’ age is more than or equal to a time limit r, it is replaced by a new one; otherwise, replaced by a used one. Obviously, if $r = T$, this policy becomes the block replacement policy. Nakagawa (1981) presented modifications to the ‘‘periodic replacement with minimal repair at failure’’ policy. The three policies all establish a reference time $T0$ and periodic time T^*. If failure occurs before $T0$, then minimal repair occurs. If the unit is operating at time T^*, then replacement at time T^*. If failure occurs between $T0$ and T^*, then: (Policy I) the unit is not repaired and remains failed until T^*; (Policy II) the failed unit is replaced by a spare unit until T^*; (Policy III) the failed unit is replaced by a new one. In all these three policies, the policy decision variables are $T0$ and T^*. Clearly, if $T0 = T^*$, Policies I, II, and III all become the ‘‘periodic replacement with minimal repair at failure’’ policy. If $T0 = 0$, Policy III becomes the block replacement policy. Nakagawa (1980) also makes an expansion to the block replacement policy. In his policy, a unit is replaced at times kT ($k = 1,2$---) independent of the age of the unit. Chun (1992) studies determination of the optimal number of periodic PM’s under a finite planning horizon. Dagpunar and Jack (1994) determined the optimal number of imperfect PMs for a finite horizon. Wang and Pham (1999) extend the block replacement policy. In their policy, a unit is imperfectly repaired at failure if the number of repairs is less than N (a positive integer). Upon the Nth imperfect repair at failure, the unit is preventively maintained at kT ($k = 1,2$---) where the constant $T > 0$.. If the repair at failure and PM are perfect and $N = \infty$, this policy reduces to the block replacement policy. Maintenance policies of the periodic PM policy are summarized in Table II.

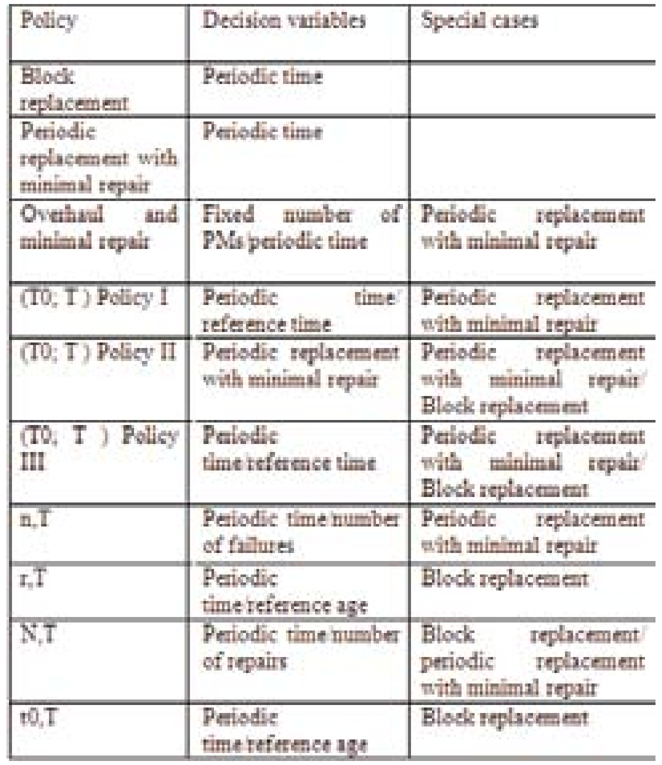
C. Failure Limits Policy

Under the failure limit policy, PM is performed only when the failure rate or other reliability indices of a unit reach a predetermined level and are corrected by repairs. This PM policy makes a unit work at or above the minimum acceptable level of reliability. Lie and Chun (1986) formulate a maintenance cost policy where PM is performed whenever a unit reaches the predetermined maximum failure rate, and are corrected by minimal repair. Bergman (1978) presented a failure limit policy in which replacement are based on measurements of some increasing state variable accumulated damage or stress. Other research on this policy are done by Malik (1979), Canfield (1986), Jayabalan and Chaudhuri (1992a), Jayabalan and Chaudhuri (1992c), Jayabalan and Chaudhuri (1995), Chan and Shaw (1993), Suresh and Chaudhuri (1994), Monga *et al.* (1997), Pham and Wang (1996). Love and Guo (1996) studied failure limit policy for preventive maintenance decisions under Weibull failure rates. The policies are summarized in Table III.

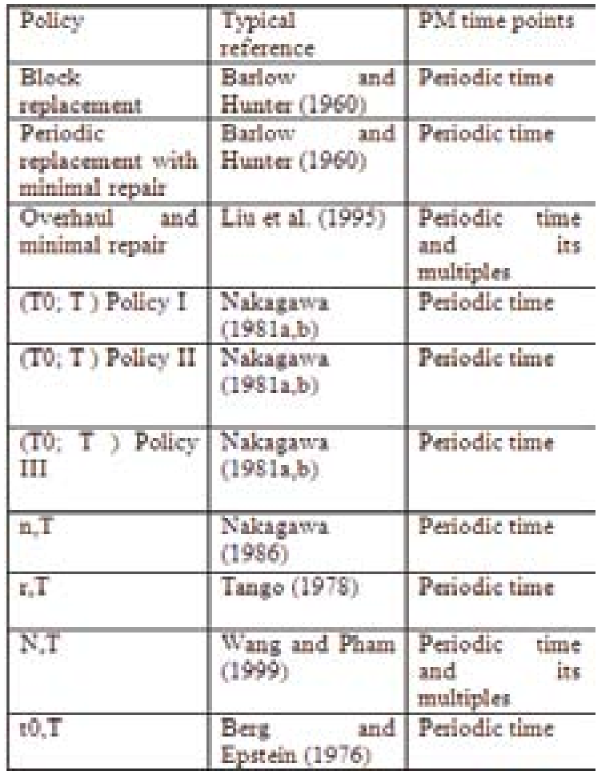
IV. Sequential PM Policy

A unit is preventively maintained at unequal time intervals under the sequential PM policy. An early sequential PM policy is designed by (Barlow and Proshan, 1965). Under this sequential policy, the age for which PM is scheduled is no longer the same following successive PMs, but depends on the time still remaining. Nguyen and Murthy (1981) introduce a sequential policy which calls for a PM by some reference time t_i, where t_i, is the maximum time that a unit should be left without maintenance after the $(i-1)$th repair (time from the last repair or replacement). In this policy, a unit is replaced after $(k-1)$ th repairs. It is repaired at the time of k th repair of failure or at age t_i. The decision variables are k and t_i, (for $i = 1 \ldots ; k$). If $k = 1$, this sequential policy reduces to the age replacement policy. Nakagawa (1986, 1988) discusses a sequential PM policy where PM is done at fixed intervals X_k (for $k = 1; 2;$---- N). The unit is replaced at the Nth PM and failures between PMs are corrected by minimal repairs. The policy decision variables are N and X_k ($k = 1, 2$ --- N). Nakagawa (1986, 1988) also presented two examples for this. Nguyen and Murthy (1981) study this policy and showed if $N = 1$, this Sequential policy reduces to the ‘‘periodic replacement with minimal repair at failure’’ policy and are different from the failure limit policy in that it controls X_k lengths directly but the failure limit policy controls failure rate, reliability, etc. Kijima and Nakagawa (1992) developed a sequential PM policy using an accumulated damage concept.

Table II Summary of Periodic PM Policies

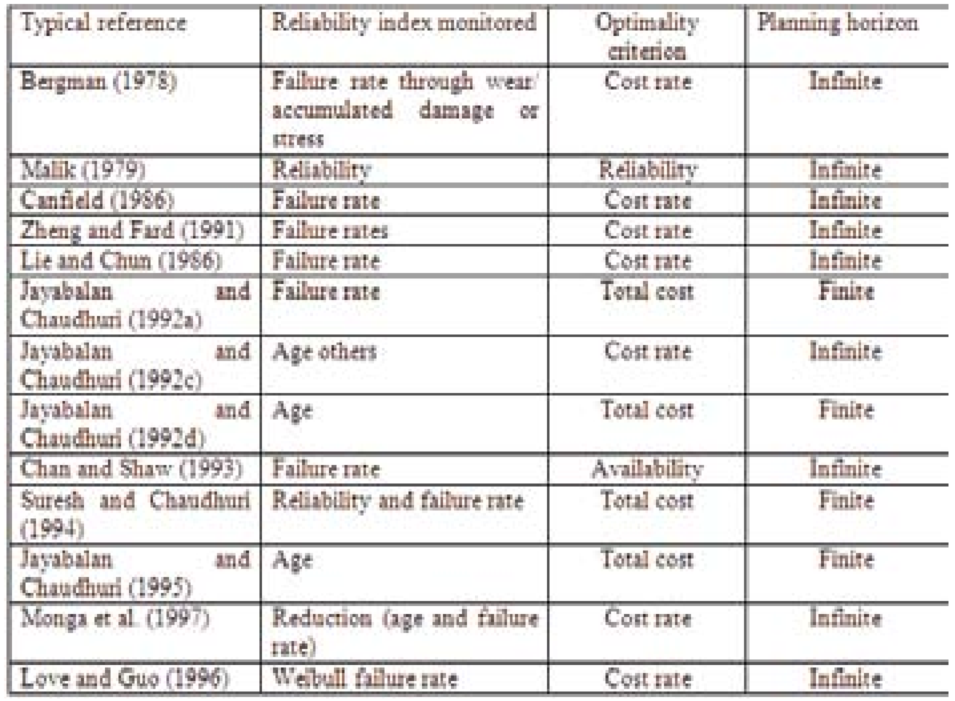


Policy	Decision variables	Special cases
Block replacement	Periodic time	
Periodic replacement with minimal repair	Periodic time	
Overhaul and minimal repair	Fixed number of PMs/periodic time	Periodic replacement with minimal repair
(T0; T) Policy I	Periodic time/ reference time	Periodic replacement with minimal repair
(T0; T) Policy II	Periodic replacement with minimal repair	Periodic replacement with minimal repair/ Block replacement
(T0; T) Policy III	Periodic time/reference time	Periodic replacement with minimal repair/ Block replacement
n,T	Periodic time/number of failures	Periodic replacement with minimal repair
r,T	Periodic time/reference age	Block replacement
N,T	Periodic time/number of repairs	Block replacement/ periodic replacement with minimal repair
t0,T	Periodic time/reference age	Block replacement



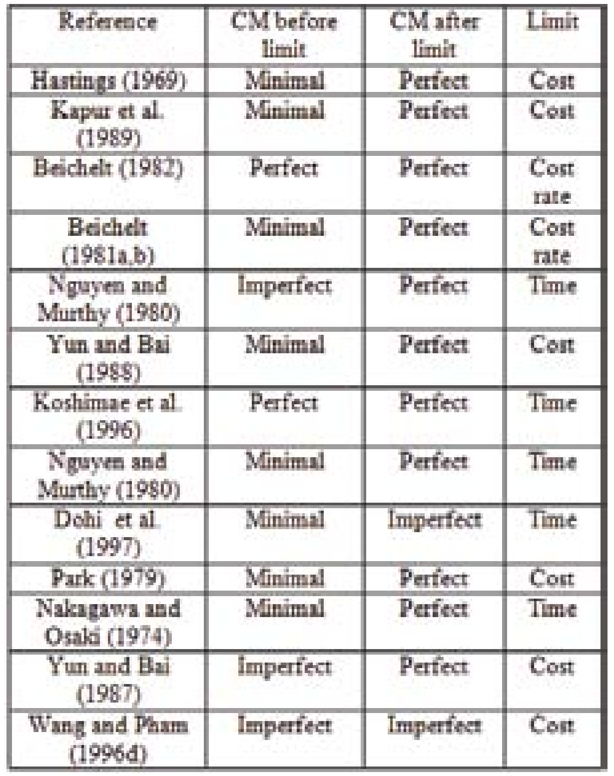
Policy	Typical reference	PM time points
Block replacement	Barlow and Hunter (1960)	Periodic time
Periodic replacement with minimal repair	Barlow and Hunter (1960)	Periodic time
Overhaul and minimal repair	Liu et al. (1995)	Periodic time and its multiples
(T0; T) Policy I	Nakagawa (1981a,b)	Periodic time
(T0; T) Policy II	Nakagawa (1981a,b)	Periodic time
(T0; T) Policy III	Nakagawa (1981a,b)	Periodic time
n,T	Nakagawa (1986)	Periodic time
r,T	Tango (1978)	Periodic time
N,T	Wang and Pham (1999)	Periodic time and its multiples
t0,T	Berg and Epstein (1976)	Periodic time

Table III Summary of failure limit policies



Typical reference	Reliability index monitored	Optimality criterion	Planning horizon
Bergman (1978)	Failure rate through wear/ accumulated damage or stress	Cost rate	Infinite
Malik (1979)	Reliability	Reliability	Infinite
Canfield (1986)	Failure rate	Cost rate	Infinite
Zheng and Fard (1991)	Failure rates	Cost rate	Infinite
Lie and Chun (1986)	Failure rate	Cost rate	Infinite
Jayabalan and Chaudhuri (1992a)	Failure rate	Total cost	Finite
Jayabalan and Chaudhuri (1992c)	Age others	Cost rate	Infinite
Jayabalan and Chaudhuri (1992d)	Age	Total cost	Finite
Chan and Shaw (1993)	Failure rate	Availability	Infinite
Suresh and Chaudhuri (1994)	Reliability and failure rate	Total cost	Finite
Jayabalan and Chaudhuri (1995)	Age	Total cost	Finite
Monga et al. (1997)	Reduction (age and failure rate)	Cost rate	Infinite
Love and Guo (1996)	Weibull failure rate	Cost rate	Infinite

Table IV Summary of repair limit policies



Reference	CM before limit	CM after limit	Limit
Hastings (1969)	Minimal	Perfect	Cost
Kapur et al. (1989)	Minimal	Perfect	Cost
Beichelt (1982)	Perfect	Perfect	Cost rate
Beichelt (1981a,b)	Minimal	Perfect	Cost rate
Nguyen and Murthy (1980)	Imperfect	Perfect	Time
Yun and Bai (1988)	Minimal	Perfect	Cost
Koshimae et al. (1996)	Perfect	Perfect	Time
Nguyen and Murthy (1980)	Minimal	Perfect	Time
Dohi et al. (1997)	Minimal	Imperfect	Time
Park (1979)	Minimal	Perfect	Cost
Nakagawa and Osaki (1974)	Minimal	Perfect	Time
Yun and Bai (1987)	Imperfect	Perfect	Cost
Wang and Pham (1996d)	Imperfect	Imperfect	Cost

Reference	Optimality criterion	Planning horizon
Hastings (1969)	Cost rate	Infinite
Kapur et al. (1989)	Cost rate	Infinite
Beichelt (1982)	Cost rate	Infinite
Beichelt (1981a,b)	Cost rate	Infinite
Nguyen and Murthy (1980)	Cost rate	Infinite
Yun and Bai (1988)	Cost rate	Infinite
Koshimae et al. (1996)	Cost rate	Infinite
Nguyen and Murthy (1980)	Cost rate	Infinite
Dohi et al. (1997)	Cost rate	Infinite
Park (1979)	Cost rate	Infinite
Nakagawa and Osaki (1974)	Cost rate	Infinite
Yun and Bai (1987)	Cost rate	Infinite
Wang and Pham (1996d)	Availability/cost rate	Infinite

V. REPAIR LIMIT POLICY

When a unit fails, the repair cost is estimated and repair is undertaken. If the estimated cost is less than a predetermined limit; otherwise, the unit is replaced. This is called the repair cost limit policy, as introduced by Gardent and Nonant (1963) and Drinkwater and Hastings (1967). Beichelt (1982) examines repair cost limit policy and uses the repair cost per unit time as a criterion of replacement or repair. Yun and Bai (1987) propose a repair cost limit policy in which when a unit fails, the repair cost is estimated and repair is undertaken if the estimated cost is less than a predetermined limit. This policy is generalized by Drinkwater and Hastings (1967). The repair time limit policy is proposed by Nakagawa and Osaki (1974) in which a unit is repaired at failure: if the repair is not completed within a specified time T, it is replaced by a new one. Otherwise the unit is put into operation; where T is called repair time limit. Nguyen and Murthy (1980) studied a repair time limit replacement policy in which there are two types of repair – local and central repair. The local repair is imperfect while the central repair is perfect, which may take a longer time. Dohi *et al,* 1997 considered a generalized repair time limit replacement problem and proposed a solution to estimate the optimal repair time limit. Koshimae *et al.* (1996) considered another repair time limit policy. Under this policy, when the original unit fails, the repair is started immediately. If the repair is completed in a time limit t0, then the repaired unit is installed as soon as the repair is finished. On the other hand, if the repair time is greater than the time limit t0, the failed unit is scrapped and a spare is ordered immediately. The policy decision variable is the repair time limit t0.The repair limit policy and its extensions are summarized in Table IV.

VI. REPAIR NUMBER COUNTING AND REFERENCE TIME POLICY

Morimura and Makabe (1963) introduced a policy where a unit is replaced at the k^{th} failure. The first k-1 failures are removed by minimal repair. Upon replacement, the process repeats. This policy is called repair number counting policy. The policy decision variable is k. Later, Morimura (1970) extends this policy by introducing another policy variable T critical reference time. Under this policy, all failures before the k^{th} failure are corrected with minimal repair. If the k^{th} failure occurs before an accumulated operating time T, it is corrected by minimal repair and the next failure induces replacement.

But if the k^{th} failure occurs after T, it induces replacement of the unit. The policy decision variables are k and T. If the policy decision variable T is zero, this policy reduces to the repair number counting policy. The repair number counting policy is examined by Jack (1991) performing imperfect repair on failure, and replacement upon the k^{th} failure. A policy similar to this policy is investigated by Park (1979) in which a unit is replaced at the k^{th} failure and minimal repairs are performed for the first $(k-1)^{th}$ failures. Lam (1988), and Stadje and Zuckerman (1990) investigated the repair number counting policy. Muth (1977) examines a replacement policy, similar to the reference time idea of Morimura (1970) in which a unit is minimally repaired up to time T and replaced at the first failure after T. This policy is referred to as reference time policy. Makis and Jardine (1992) introduced policy in which a unit can be replaced at any time and at the n th failure the unit is replaced or undergo an imperfect repair. Under different conditions, this policy can reduce to the repair number counting, reference time and "periodic replacement with minimal repair at failure" policies. In general, the repair number counting policy is effective when the total operating time of a unit is not recorded or time consuming and costly to replace a unit. Phelps (1981) compared the "periodic replacement with minimal repair at failure" policy with other policies like (Barlow and Hunter, 1960), the repair number counting policy (Morimura and Makabe, 1963, Park, 1979), and (Muth,1977 the reference time policy given an increasing failure rate. Phelps (1981) shows that the reference time policy, replacing after the first failure is the optimal of the three policies in terms of the long-run cost rate. The repair number counting policy is more economical than the "periodic replacement with minimal repair at failure" policy and are mainly based on counting the number of repairs and/or reference time, but the age-dependent PM policy and periodic PM policy rely on PM times. In the repair number counting and reference time policy, number of repairs or reference time are policy decision variable(s). In the age-dependent PM policy and periodic PM policy, PM time is one of the policy decision variables.

VII. On the maintenance policies for single-unit systems

The age-dependent PM policy and periodic PM policy have received much more attention in the literature. The noted authors are (McCall (1963), Barlow and Proshan (1965, 1975), Pierskalla and Voelker (1976), Osaki and Nakagawa (1976), Sherif and Smith (1981), Pham and Wang (1996) under these two kinds of maintenance policies. Detailed comparisons on the age and block replacement policies can be found in Barlow and Proshan (1965, 1975). Berg and Epstein (1978) compare three types of replacement policies: age, block, failure replacement policies and provided a heuristic rule for choosing the best one. Block *et al.* (1990) compared the block replacement policy and "periodic replacement with minimal repair at failure" policy. In Block *et al.* (1993), comparisons are also made among the age replacement policy, block replacement policy, and repair limit policy. The failure limit policy, repair limit policy, and sequential policy are more practical, but there has been much less research done on it. One of the disadvantages of the failure limit policy and sequential policy is that their PM intervals are not equal. The periodic PM policy is perhaps more practical than the age-dependent PM policy since it does not require keeping records on unit usage. The block replacement policy is more wasteful than the age replacement policy since a unit of "young" age might be replaced at periodic times. The maintenance policies have become more and more general because they include some previous policies as special cases. This is reflected in Tables I and II. The maintenance cost may be a function of unit age and number of repairs already performed on the unit. Frenk *et al.* (1997) established a general method for modeling complicated maintenance costs. The current research seems to intend to use two or more of them as policy decision variables in a single policy.

VIII. Maintenance Policies of Multi-Unit Systems

Multi unit systems are those systems with a number of subsystems. Optimal maintenance policies for such systems reduce to those with a single subsystem only. In this case, maintenance decisions are independent, and the "optimal" maintenance policy is to employ one of the six classes of maintenance policies for each subsystem. The optimal maintenance action for a given subsystem depends on the states of all subsystems in the system: the failure of one subsystem results in the possible opportunity to undertake maintenance on other subsystems (opportunistic maintenance). Economic dependency is common in most continuous operating systems. For this type of system, the cost of system unavailability may be much higher than maintenance costs. Therefore, there is often a great potential for cost savings by implementing an opportunistic maintenance policy. Currently, there is an increasing interest in multicomponent maintenance policies and models as pointed out by Van Der Duyn Schouten (1996). Next it is summarized for maintenance policies of multi-unit systems. Cho and Parlar (1991) surveyed the multi-unit system maintenance models. Dekker *et al's* review is focused on economic dependence of models. This survey is emphasized on classifications and characteristics of maintenance policies (Dekker *et al.,* 1997).

IX. Group Maintenance Policy

The problem of establishing group maintenance policies, which are best from the view of system's reliability or operational cost, has received attention. One problem for group maintenance policies is to establish the units that should be replaced when a failure occurs. A second class has been concerned with reducing costs by including redundant parts into systems design. A third class has been concerned with for systems of independently operating machines, all of which are subject to stochastic failures (Ritchken and Wilson, 1990). There are three existing group maintenance policies.

The first policy, referred to as a T age group replacement policy, for a group replacement at the age of T. The second is m-failure group replacement policy, for a system inspection after m failures have occurred. The third policy combines the advantages of the m-failure and T-age policies. This policy, referred to as an (m, T) group replacement policy, calls for a group replacement when the system is of age T, or when m failures have occurred. The (m, T) group replacement policy requires inspection at either the fixed age T or the time when m machines have failed . At an inspection, all failed units are replaced with new ones and all functioning units are serviced so that they become as good as new. Gertsbakh (1984) introduces a policy in which a system has n identical units with exponential lifetimes, and is repaired when the number of failed units reaches some prescribed number K.Vergin and Scriabin (1977) propose a (n,N) policy. Love *et al.* (1982) establish another group replacement policy. Under this policy a vehicle is replaced when repair cost for the vehicle exceeds a pre-set repair limit . Sheu and Jhang (1997) propose a 2-phase group maintenance policy for a group of repairable items. The time interval (0; T] is defined as the first phase, and the timer interval (T , T + W] is defined as the second phase. As individual units fail, individual units have two types of failures. Type I failures are removed by minimal repairs, whereas Type II failures are removed by replacements or are left idle.

X. Opportunistic maintenance policies

Maintenance of a multicomponent system differs from that of a single unit system. One is economic dependence, another is failure dependence, or correlated failures. (Nakagawa and Murthy, 1993). Berg (1976, 1978), suggests a preventive replacement policy for a machine with two identical components which are subject to exponential failure. Under this policy, upon a component failure the other and the failed one is replaced by a new one if its age exceeds a pre-determined control limit L. Berg (1978) extends it to such an policy: both units are replaced either when one of them fails and the age of the other unit exceeds the critical control limit L, or when any of them reaches a predetermined critical age S. This policy will become two independent age replacement policies if $L=\infty$. Zheng and Fard (1991) examine an opportunistic maintenance policy based on failure rate tolerance for a system with k different types of units. A unit is replaced either when the hazard rate reaches L or at failure with the failure rate in a predetermined interval L-u. Kulshrestha (1968) presented policy in which there are two classes of units. Class 1 contains M standby redundant units so that upon the failure of the currently operating class-1 units, a standby takes over. When all the class-1 standbys have failed, the system suffers catastrophic failure. The class-2 units, on the other hand, form a series system; if one of them fail, the system suffers a minor breakdown. When a minor breakdown occurs, there is a chance for opportunistic repair of class-1 units which have failed. Pham and Wang (2000) propose two new (τ,T) opportunistic maintenance policies for a k-out-of n system. In these two policies, minimal repairs are performed on failed components before time τ and CM of all failed components is combined with PM of all functioning ones after τ. The policy decision variables are τ and T. They extended these two policies by including the third decision variable the number of failed components to start CM, considering the k-out-of-n system may still operate even if some of its components have failed. Dagpunar (1996) introduces a policy where replacement of a component within a system is available at an opportunity. Rander and Jorgenson (1963) and Wang (2001) investigated an opportunistic preparedness maintenance of multi-unit systems with (n+1) subsystems. Wang. (2001) examine such a preparedness policy: (i) If subsystem i fails when the age of subsystem 0 is in the time interval (0, ti) replace subsystem i alone at a cost of Ci and at a time of Wi (i = 1, 2 ... N). (ii) If subsystem i fails when the age of subsystem 0 is in the time interval (ti T) replace subsystem i and do perfect PM on subsystem 0i (i = 1, 2 . . . N) The total maintenance cost is C0i and total maintenance time is w0i (iii) If subsystem 0 survives until its age x =T perform PM on subsystem 0 alone and at a maintenance time of w0 (at x = T PM is imperfect).

XI. Optimal maintenance policies

Maintenance aims to improve system availability and MTBF, to reduce failure frequency and downtime. However, since maintenance incurs cost, to reduce maintenance cost is also necessary. Generally, an optimal system maintenance policy may be the one which either (a) minimizes system maintenance cost rate, (b) maximizes the system reliability measures, (c) minimizes system maintenance cost rate while the system reliability requirements are satisfied, or (d) Maximizes the system reliability measures when the requirements for the system maintenance cost are satisfied.

Fig. 2 shows various factors which may affect an optimal maintenance policy. It is noted that for a series system there exist some shut-off rules.

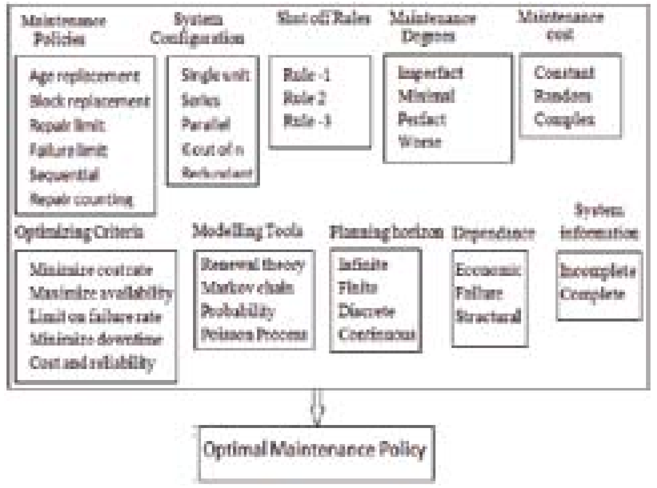


Fig. 2 Maintenance policy and its influence factors

Besides, it is worthwhile to mention the following points: 1. All these methods for a single-unit system will be the basis for the analysis of a multicomponent system. 2. In most existing literature on maintenance theory, the maintenance time is assumed to be negligible. This assumption makes availability, MTBF and MTTR modeling impossible or unrealistic. 3. The structure of a system must be considered to obtain optimal system reliability performance and optimal maintenance policy.

X. Conclusion

The foregoing survey describes the literature related to maintenance policies for multi and single unit systems. The methods of finding the surveyed papers include journal, conference paper and books search. Although the authors of this survey have tried to reference as many articles as possible, still there are other relevant papers which should have been included. Also, in some cases a brief description has been given. The survey has three distinct features.

1. Emphasis on work done in different periods. 2. Covers most maintenance policies. 3. Alternative ways to review a paper of his /her interest for future survey. The paper will help to have a basic knowledge about the maintenance policies and policy appropriate to their organization and the policy is available from reference list.

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