Journal of Mining and Environment (JME) Vol. 12, No. 3, 2021, 753-767

Shahrood University of Technology

Iranian Society of Mining Engineering (IRSME)

Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

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Expected Proportional Hazard Model in Preventive Maintenance

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Article Info

Received 8 May 2021
Received in Revised form 3 July 2021
Accepted 8 July 2021
Published online 8 July 2021

DOI:10.22044/jme.2021.10812.2051

Keywords

Reliability
Maintenance
Expected Proportional Hazard Ratio Model
Proportional Hazard Model
Hybrid Imperfect PM Model

Abstract

Whether directly in the form of expenses or indirectly, the objective of maintenance in the mining industry is self-evident in time losses and loss of production. In this paper, the reliability-based maintenance is examined with a different insight than before. The system goes back to the Good As New (GAN) state or too Bad As Old (BAO) maintenance state; why so, the maintenance of the system shifts to the midrange state. On the other hand, the implementation of repairs is strongly influenced by the environmental factors that are known as the “risk factors”. Therefore, an analysis requires a model that integrates two basic elements: (1) incompleteness of the maintenance effect and (2) risk factors. Thus, an extensive proportional hazard ratio model (EPHM) is used as a combination of the Proportional Hazard Model (PHM) and the Hybrid Imperfect Preventive Maintenance model (HIPM) in order to analyze these elements. In this regards, four different preventive maintenance strategies are proposed. All four strategies are time-based including constant interval or periodic (the first and second strategies) and cyclic interval (the third and fourth strategies). The proposed method is applied for a Komatsu HD785-5 dump-truck in the Songun copper mine as a case study. The PM intervals with a mean value of risk factors for the four activities to reach the 80% reliability for the first and second strategies are about 5 and 48 hours. These intervals for the third strategy are calculated as 48.36, 11.58, 10.25, and 9.035, and for the fourth strategy are 5.06, 4.078, 3.459, and 1.92.

List of idioms and abbreviations

Idiom	Abbreviation	Idiom	Abbreviation
Age reduction factor	ARF	Military Handbook	MIL-Hdbk
Autocorrelation function	ACF	Non-homogeneous poisson process	NHPP
Bad As old	BAO	Power low process	PLP
Expected proportional hazard ratio model	Ex-PHM	Preventive maintenance	PM
Extensive proportional hazard ratio model	EPHM	Proportional hazard model	PHM
Proportional hazard assumption	PH-assumption	Reliability limited preventive maintenance	RLPM
Good as new	GAN	Stratified Cox regression model	SCRM
Hazard rate increase factor	HRIF	Hybrid imperfect preventive maintenance model	HIPM
Independent and identically distributed	iid	Time between failures	TBFs

1. Introduction

In the mining industry, maintenance allocates a significant share of the total operating costs. Succeeding in implementing an advanced maintenance technology requires a strong theoretical foundation and adequate awareness of the hardware and software involved. Maintenance is one of the high but scalable mining industry costs. In addition, experience has shown that the range of mineral equipment maintenance costs varies from 20% to more than 35% of the total operating costs of the mine, and is steadily increasing [1]. Despite the extensive efforts in

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analyzing and optimizing the major mining processes, little attention has been paid to optimizing the maintenance processes. At the same time, the optimum maintenance management and significantly reducing costs and improving the reliability of equipment increase the useful life of the equipment, and thereby, increase the return on investment costs and allow for a higher profitability than the fixed investment [2]. The system's reliability is analyzed based on the operating time, which is also directly determined by failures. One of the consequences of failures in manufacturing the systems and industrial processes is the drop in production, and as a result, the failure to realize the expected capacity and the delay in delivering goods to the customer, and in the long run, reduction of the market share. Another consequence is a waste of excess, resulting in a waste of materials and resources and additional costs in production. This will always increase the finished product price, decreased quality, and credit loss due to capacity loss due to optimal capacity [3]. The concept of maintenance based on reliability in mineral works was introduced in 1992 by Kumar and Klefsjo [4,5]. In 2004, Samantha et al. after analyzing the reliability of the Load-Haul-Dump (LHD) system by the classical method calculated the maintenance spreads for different levels of the maintenance [6]. Javad Barabadi and Kumar performed a similar process in 2005 for the underlying sub-systems of riddle and conveyor from the Smashing Department [7]. In the following years, the same trend was again carried out by Javad Barabadi and Hosseini et al. on the Smash Department, the Conveyor Sinker, Tire, and Drilling Machine. In all of these studies, a maintenance strategy was proposed by assuming two modes of Good As New (GAN) state or Bad As Old (BAO) [2,8–14]. On the other hand, one of the key challenges in optimizing the maintenance policy for different systems is to consider the environmental conditions, affecting both the failure conditions and the operation times (the Uptime and the Downtime of the machine). Therefore, the system's reliability is also a function of the time and the environmental conditions of the operating system; the study requires a framework that includes technical, operational, commercial, managerial, in general, known as the “risk factors” [15]. In the 1970s, the regression models were proposed in order to provide better estimates of reliability based on their ability to input the risk factors into computations [16,17]. These risk factors are randomly changed to change the time of failure [18,19]. The risk-based models in the reliability analysis are primarily based on the Proportional Hazard Models (PHMs). PHM is a non-parametric or semi-parametric approach developed by Cox (1972) for the medical survival data [20]. This model is a valuable statistical process used to estimate the risk of failure due to the conditions and the system's environment. This model assumes that the component or sub-system risk rate function combines its underlying risk function and a term that includes the effects of risk factors [21]. For more information on the maintenance analysis using the regression models, refer to these sources [22–24]. The next challenge with maintenance optimization is to introduce the effects of maintenance execution on the system since the system does not return to the new state (or GAN) nor will it be in a bad condition before the repair (or BAO). This type of maintenance is an imperfect maintenance that the system, after executing repairs, will be in an interstitial situation. In 1996, Wang and Pham looked closely at the 30-year history of this type of maintenance [25]. In the following years, the researchers such as [10,23,26–28] researched the concerning nuclear power plants, ball grid array, hypothetical electrical, and turbo-pumps. Recently, the athours such as Zaki et al., Rod et al., and Mottahedi et al. have used the PHM and extention of PHM in the system performance index analysis [29–32]. However, the above research work could only cover some of the parameters involved in the maintenance programming because part of the research work only determines the reliability of time data, and ignores the environmental impact at the outset, while the environmental conditions are very capable of controlling the operation of the system and the implementation of the repairs. Typically, doing repairs for a maintenance team in one day at 18 °C with ordinary clothes would be much less time consuming than doing the same repairs at -2 °C with several warm clothes. Alternatively, sending the supplies and parts required to run the maintenance on a dry day on a dry road is much easier than sending the same stuff on a foggy day with muddy road. On the other hand, in the case of repairs for a part of the system, one should not expect the whole system to return to a new state, which is also ignored in many research works. For example, in major repairs to the engine of a generator with a damaged gas pump, it would not be expected that the entire system would work well because the diesel pump should be repaired. Hence, the actual programming of the maintenance requires a model that can cover all of these cases. In this paper, a comprehensive approach is proposed for the simultaneous analysis of the environmental conditions and the implementation of the violations of the system. In this process, the EXpected Proportional Hazard ratio Model (Ex-PHM) is included as a combination of two effective branches in maintenance programming. The first branch of the system performance and the impact of environmental conditions on that dominated by PHM, and the second branch of the effect of how the maintenance is implemented on the state of the system, which is dominated by the Hybrid Imperfect Preventive Maintenance (HIPM) model in the analyzes. For this purpose, this article was arranged in these three main sections:

- Section 1: Explanation of the maintenance and proposed hybrid model;
- Section 2: An analysis of the maintenance program of the dump truck system from the Sungun copper mine with the proposed model;
- Section 3: Conclusions.

Also the following limitations are considered in this paper:

- All the observable risk factors are identified;
- The effects of the unobservable risk factors are ignored;
- The system is repairable.

2. Theory of Time-based Preventive Maintenance Policies

Maintenance is defined as combining all the technical and management, and supervisory activities in order to ensure that a component expects the activity, equipment or system to be done when required [33]. The most important elements of maintenance engineering that can be mentioned are [26]:

a. Purpose: items such as maximization of mean system availability in unlimited time horizons, minimization of loss of production due to a limited period, average minimization rate of maintenance costs in each period of the operation in a limited period.

b. Maintenance policy: such as periodically policy, controlled policy, and continuous policy.

c. Quality or quantity of maintenance efficacy: Maximum preventive maintenance, accomplishment that turns the system to the GAN terms, and minimum preventive maintenance accomplishment that turns the system to the BAO terms.

d. Depreciation attributes study: such as lifetime distributions, statistical models, Markov.

e. Maintenance limitations: such as maintenance resources and spare parts.

For maintenance effectiveness, the related activities must execute in a specific framework. The main maintenance strategies are as follow:

- Corrective maintenance: maintenance execution after failure for restoration of an instrument to do the required activity conditions.
- Preventive maintenance: maintenance execution in designated intervals based on the specific criteria to reduce the likelihood of failure or prevention of degradation in the functionality of a device [34]. This type of maintenance is divided into the time-based and condition-based categories [8,35].
- No maintenance design: the system and components designed with this strategy do not require any maintenance, for example, no need for lubrication bearings [9].

Typically, the effects of maintenance activity and life-affirmation on the state of components are defined differently. In the first case, it is assumed that the component after the maintenance returns to the GAN state so that the elapsed time after applying the maintenance is zero [23]. This is the definition of maximum maintenance. Major overhauls in the factories or the entire system change are examples of this kind of maintenance [25,36].

In the second case, it is assumed that the maintenance drapes the system in the BAO condition. It means that the sub-system after the maintenance is approximately equal to its position before it is applied [23]. In other words, with this maintenance, the system failure rate returns to the state before the failure. These types of repairs are known as minimum maintenance or repairs. Tire lubrication or shifting the butterfly belt are examples of these conditions because the machine's overall risk does not necessarily change [25,36].

Other modes of repairs are known as "bad" repairs or maintenance. In this case, the maintenance activity can increase the risk or reduce the system life but failure does not occur in the system so that, in this case, the system condition after the maintenance is worse than the initial state. The next type of repair can be considered as the worst repair or maintenance; in this case, the maintenance activity causes a failure in the system. Repairing a not damaged part, flawed repair of the damaged piece, repairing the broken piece, disturbing the system settings, incorrect failure location detection, and performing maintenance at inappropriate times are examples of bad maintenance worst maintenances [25,36].

The latest type of maintenance, which is also the main topic of maintenance, is imperfect maintenance or repairs. These two types, maximal and minimal maintenances, are not enough to describe the actual effects of maintenance operations and the lifetime component or system repair. In fact, after every maintenance activity, the piece's condition under repair depends on the maintenance effect; it somewhat improves (the system gets younger). This effect is not so ideal that the piece returns to the GAO state and not to the extent that it reaches the BAO state. Therefore, this type of maintenance is referred to as "imperfect repairs or maintenance". This model is the BAO and GAN models [23], and transmits the system to a state between GAN and BAO. Setting the engine is an example of this type of maintenance. One of the most important and common types of maintenance strategy in the equation to imperfect maintenance in the today's industry is defective maintenance, which has been widely studied to incorporate its effects into maintaining policies. One of the challenges of optimizing the maintenance policy is to consider the changing environmental conditions using the statistical models, in particular the regression models such as PHM and Stratified Cox Regression Model (SCRM). Because the system under different environmental conditions has different failure rates, each mode must be examined separately. Under such circumstances, a PM control policy is proposed with a reliability limit (RLPM) at the sub-system level that can cover the impact of imperfect PM activity and environmental conditions. For this purpose, the Extended Proportional Hazard Model (EPHM) will be used. This is the dual combination model of PHM and the hybrid model of imperfect PM and variable environmental conditions. For this purpose, the "EXpected Proportional Hazard Model" (Ex-PHM) will be used. This model combines PHM and a hybrid model of imperfect PM (HIPM) [26]. The PHM model is expressed as follows:

$$\lambda(t.z) = \lambda(t)exp(\alpha z(t)) \tag{1}$$

In this model, the use of environmental conditions of system performance as a risk factor (z) enables PHM to assess the impact of environmental conditions on the probability of failure. The HIPM hazard rate function is established as Eq. (2) [27,37].

$$\lambda_n\left(t' + \sum_{j=1}^{n} T_j\right) = A_n(t)\lambda(t' + b_n y_n) \tag{2}$$

In this equation, λ_n is the system risk rate function after the nth and before (n + 1) the PM activity, t' is the random time after the jth activity of PM and before the (j + 1)th activity of PM, A_n is the hazard rate increase factor (HRIF) caused by the jth activity of PM obtained from the following equation, in which $a_j > 0$ and $a_0 = 1$ [27,38]:

$$A_n = a_0 \times a_1 \times \ldots \times a_n = \prod_{j=0}^{n} a_j \tag{3}$$

a_0 is the age reduction factor (ARF) due to the nth activity of PM, and y_n is the useful life of the system expressed before the nth activity of PM as Eq. (4).

$$\begin{aligned} y_n &= T_n + b_{n-1}y_{n-1} = \\ &T_n + b_{n-1}(T_{n-1} + b_{n-2}y_{n-2}) = \\ &T_n + b_{n-1}T_{n-1} + \cdots + (\prod_{h=1}^{n-1} b_j)T_1 \end{aligned} \tag{4}$$

In this equation, $0 \leq b_1 \leq b_2 \leq \cdots \leq b_n \leq 1$, and $y_1 = T_1$ [38]. ARF measures the PM impedance effects, which returns the system to a younger state but not zero. In this state, the start of the system is observed after an imperfect PM activity. On the other hand, HRIF is a measure for the persistent effects of the imperfect PM activity, leading to a moderate increase in the likelihood of failure. These effects are cumulative, and are intensified by performing more activities on PM so that this kind of Ex-PHM model is a combination of PHM and HIPM. The general form of this model is expressed by Eq. (5) [26].

$$\begin{aligned} &\lambda_n(t' + \sum_{j=1}^{n} T_j . z(t' + \sum_{j=1}^{n} T_j)) = \\ &A_n(t)\lambda(t' + b_n y_n)exp(\alpha z\left(t' + \sum_{j=1}^{n} T_j\right) \end{aligned} \tag{5}$$

In this regard, λ_n is the system risk rate function after the nth PM and before the n + 1 PM. The Ex-PHM model has PHM and HIPM to assess the effects of the PM activity, and allows for a joint assessment of the effects of both parameters in a framework. If (R_{jk}) represents the reliability function of the sample "j" after the k'th and before (k+1) of pm, R_{j0} is the reliability function before any PM activity. R_{jk} is expressed as follows [26]:

$$R_{jk}\left(t'\sum_{j=1}^{n}T_j\,.\,z\left(t'+\sum_{j=1}^{n}T_j\right)\right)= -\int_0^{t'}\lambda_{jk}\left(\upsilon+\sum_{j=1}^{k}T_k\,.\,z_j\left(\upsilon+\sum_{j=1}^{k}T_j\right)\right)d\upsilon \quad (6)$$

In the mining and industrial works, the Weibull distribution function is one of the most used life functions in a reliability analysis. This distribution is highly flexible, and can model the failure data at an incremental or a decreasing risk rate. In Eq. (7), the form of this distribution is observed for the Ex-PHM model [26].

$$\lambda_n\left(t'\sum_{j=1}^{n}T_j\,.\,z\left(t'+\sum_{j=1}^{n}T_j\right)\right)= A_n(t)\frac{\gamma}{\eta}\left(\frac{t'+b_n y_n}{\eta}\right)^{\gamma-1} exp\left(\alpha z\left(t'+\sum_{j=1}^{n}T_j\right)\right) \quad (7)$$

In this equation, γ and η are the parameters of the shape and distribution scale of the vibe. The maximum likelihood method is used for the estimation of the parameters of Eq. (7). The estimation process is such that the parameters (η, γ, α) are based on the first event (before the first PM) without considering b_j and a_j. Then the parameters (b_1, a_1) are estimated by inserting the estimated parameters in the previous step in the probability function for the second event, and the same trend continues for (b_j, a_j) based on the (j+1)th data. On the other hand, the ARF and HRIF values can be used to access the expert systems or use some of the proposed equations in Table 1. This model will be complete when all its parameters are estimated [27].

Table 1: Different effects of PM activities [27].

Impact of imperfect PM activities	ARF & HRIF
Worse than basic conditions	$a_j=\frac{3j+1}{2j+1}.\,b_j=\frac{2j}{3j+2}$
Basic conditions	$a_j=\frac{6j+1}{5j+1}.\,b_j=\frac{j}{2j+1}$
Flawed but better than basic conditions	$a_j=\frac{10j+1}{9j+1}.\,b_j=\frac{j}{3j+1}$

The PM strategy is usually based on the reliability limitations, which is named “RLPM”. In this strategy, the implementation time of the maintenance operations is suggested in order to maintain the system's reliability at each critical interval of the operation of the network until it is changed to the critical level “r”. In this case, until failure occurs, the system is minimally repaired (restoring the system to a worker so that the risk level will be the same as the risk level was before the repairs). An example of the minimal repairs can replace minor components (small or small) from a large system with many components. In implementing the RLPM strategy, the Ex-PHM model is used to describe the system lifetime distribution. The mathematical expression of this policy is explained in Eq. (8) [23,26].

$$R_{jo}(T_j)=R_{j1}(T_1+T_2)=\cdots=R_{jN-1}\left(\sum_{j=1}^{L}T_j\right)=r \quad (8)$$

In this equation, r is the critical reliability, which, if degraded, it will be recommended to this PM value activity. L is also a continuous random number, and represents the number of PM activities before the switch. The value of r based on the Ex-PHM model is obtained from the following equation [23,26]:

$$r=exp\left(-\int_0^{T_1}\lambda_{jo}\left(\upsilon;z_j(\upsilon)\right)d\upsilon\right)= exp\left(-\int_0^{T_2}\lambda_{j1}\left(\upsilon+T_1;z_j(\upsilon+T_1)\right)d\upsilon\right) =\boldsymbol{exp}\left(-\int_0^{T_L}\boldsymbol{\lambda_{j(L-1)}}\left(\boldsymbol{\upsilon}+\sum_{j=1}^{L\_1}\boldsymbol{T_j};\boldsymbol{z_j}\left(\boldsymbol{\upsilon}+\sum_{j=1}^{L\_1}\boldsymbol{T_j}\right)\right)\boldsymbol{d\upsilon}\right) \quad (9)$$

If r = 1, the Ex-PHM equation will represent the effects of the imperfect PM table, representing the full PM model. The expansion of Eq. **Error! Reference source not found.** for the Weibull distribution is as follows [23,26]:

$$
\begin{aligned}
-ln(r) &= \int_0^{T_1} \left(\frac{\gamma}{\eta}\left(\frac{v}{\eta}\right)^{\gamma-1}\right)\exp\big(\alpha z(v)\big)\,dv \\
&= \int_0^{T_1} \left(A_1\frac{\gamma}{\eta}\left(\frac{v+b_1y_1}{\eta}\right)^{\gamma-1}\right)\exp\big(\alpha z(v+T_1)\big)\,dv \\
&= \int_0^{T_1} \left(A_{L-1}\frac{\gamma}{\eta}\left(\frac{v+b_{L-1}y_{L-1}}{\eta}\right)^{\gamma-1}\right) exp(\alpha z(v+\sum_{j=1}^{L\_1}T_j))dv
\end{aligned}
\tag{10}
$$

In the above equation, the last equation is the cumulative risk of the system (Qk) in the "j"th interval of PM [23,26]:

$$
Q_k = \int_0^{T_1} \left(A_{L-1}\frac{\gamma}{\eta}\left(\frac{v+b_{L-1}y_{L-1}}{\eta}\right)^{\gamma-1}\right) exp(\alpha z(v+\sum_{j=1}^{L\_1}T_j))dv \tag{11}
$$

The value of k = 1, 2, ..., L represents the expected number of failures in the K_{th} interval of PM.

3. Case study

In the mining industry, a considerable portion of the total operational expenses is attributed to maintenance. For an advanced maintenance technology performance to be achieved, a well-established theory and an adequate knowledge of the relative software and hardware are required. Maintenance is attributed to one of the large-scale but controllable expenses in the mining industry, which consists of nearly 30-50% of immediate mining expenses. Moreover, based on the experience, the variance domain of the mining operational expenses is 20% greater than the total mining operational expenses, which are 35%, and the figure steadily increases. Despite the best efforts dedicated to analyzing and optimizing the main mining processes, little attention has been paid to optimizing the maintenance processes.

In contrast, the optimally managing maintenance activities, more than the considerable reduction in expenses and improved equipment reliability, causes the effective lifespan of the equipment to be increased. As a result, the return rate of investment expenses is increased. Also more profitability of fixed investment is achieved. Thus it is a should for those mining companies to control these expenses, make their activities centered around those fields such as maintenance optimization, a delay of unnecessary maintenance, an improved quality of the maintenance staffs, management and control of spare parts, and use of various software and hardware that are available. In this regard, we should consider that millions of dollars invested in the maintenance engineering annually. Today, maintenance is considered asan undeniable element in giant production companies such as the copper and metal industry, cement industry, and automotive and service organizations such as mining companies. Maintenance engineering seeks to answer such questions as "How can I determine the level of the service required for a particular piece of work?", "What should I do during the maintenance?", "What is the best time to do the maintenance?", "How should maintenance be given for a component of the equipment?", etc. This treatise, the algorithm presented in Figure 1, has been used to decide on a general strategy (preventive, corrective, ...), which in the case of the Sungun Copper Mine, due to the inadequate risk of failure of the maintenance strategy, it should be done on a time-based preventive basis. In order to implement the proposed methodology, a Komatsu HD785-5 dump truck was selected from the fleet. For this sub-system, the performance parameter reliability was selected, and the environmental conditions were affected. Also for the first time, the three parameters of the system operation, the effects of environmental conditions, and how the maintenance was performed based on the minimal, imperfect or perfect integration were merged, and the most suitable intervals were proposed. Then the defective and complete preventive databases based on reliability are proposed with and without the impact of the environmental conditions.

3.1. Dump-truck reliability analysis

In the first step, the system reliability was analyzed without affecting the environmental conditions. As mentioned earlier, the trend and autocorrelation tests were used to analyze the independent and identically distributed (iid) assumption of the data. In this research work, both the analytical and graphical methods (cumulative time between failures (TBFs) for the cumulative occurrence of failures) were used in order to conduct the trend test. The autocorrelation function (ACF) method was used for the serial correlation test. The analytical method trend test result is the system at a significant level of $\alpha = 0.05$ in Table 2. The graphic diagram of the system trend is shown in Figure 2-A. This diagram shows the full compatibility between the analytical and graphical test results. As one can see, the values of the p-value in a system are larger than α; therefore, the zero hypotheses of the absence of trend are rejected in this system. In order to decide on the rejection or acceptance of the null hypothesis (= no serial correlation), the correlogram at 95% confidence level was used (Figure2-B). In this figure, the ACF values with columns and the 95% critical confidence boundary are shown for evaluating the zero hypotheses with the lines of the top and bottom lines. As it can be seen, the ACF column of step 1 for the system is 0.092, and is in the range of high-level lines in the upper and lower positions, and thus the zero assumption of the lack of serial correlation is accepted.

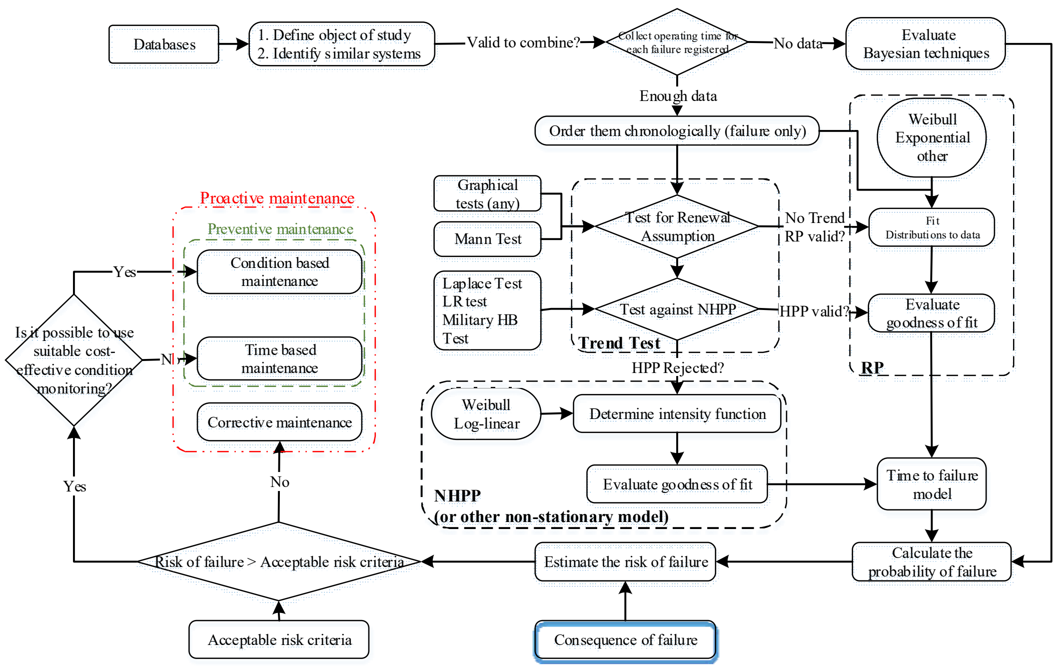

Figure 1: Methodology of reliability-based maintenance plan selection [39].

As mentioned in this paper, the power low process (PLP) method, a specific non-homogeneous Poisson process (NHPP) method, analyzes the system reliability. According to the trend tests and the serial correlation results, the iid assumption is rejected for the TBFs of the dump truck, and the NHPP method is suitable for describing the behavior of the variable failures over time. The parameters of the scale (θ) and the shape (β), according to Table 2, are 145.699 and 1.354, respectively, and the rate of risk and reliability of it will be as follow:

$$\lambda_b(t) = \left[\frac{1.354}{145.699}\left(\frac{t}{145.699}\right)^{0.354}\right] \tag{8}$$

$$R_b(t) = \left(exp\left(-\frac{t}{145.699}\right)^{1.354}\right) \tag{9}$$

Table 1: Dump-truck Statistical tests.

Trend test	**Anderson-Darling**	**Laplace's**	**MIL-Hdbk-189**
Test statistic	12.55	4.77	280.72
p-value	0	0	0
Analytical and graphical tests (Null hypothesis: no Trend)	Rejected		
Serial correlation test	**Ljung-Box Q statistic**	**T-test**	**ACF**
Test results in log.1	1.617	1.262	0.092
Test results in log.2	1.754	0.363	0.027
Analytical and graphical tests (Null hypothesis: no serial correlation)	Accepted		
iid assumption	Rejected		
Model or function	PLP	**Parameters**	
		Scale	**Shape**
		154.699	1.354

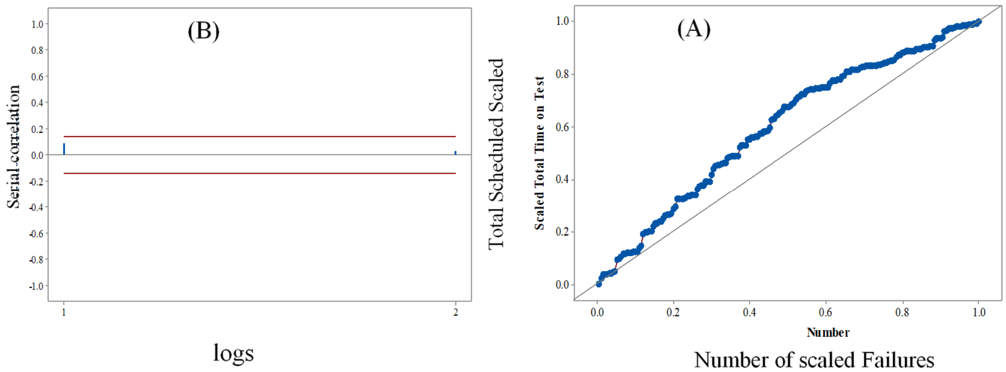

Figure 1: Graphical trend tests (A) and correlogram for different logs (B).

In determining the reliability function based on the environmental conditions, the baseline function follows the shape and scale parameters with values of 1.019 and 29.512. The analytical results of the assumption of fit are presented inTable e.

In the case of the dump track data, high values of the p-value for proportional hazard assumption (PH- assumption) in all the effective risk factors are shown the acceptance of the assumptions. Therefore, the PHM model is used for this data. Table 4 shows the regression coefficients of this model. Therefore, the function of the real risk rate (λ (t, z)) and reliability (R (t, z)) of the tire of the dump track will be as follows:

$$\lambda_c\,(t.z) = \left[\frac{1.019}{29.512}\left(\frac{t}{29.512}\right)^{0.019}\right] exp(-0.773Z_{t1} - 0.599Z_{t3} + 0.768Z_{t5} + 0.317Z_{t9} + 0.585Z_{t11}) \quad (10)$$

$$R_c(t.z) = \left(exp\left(-\frac{t}{29.512}\right)^{1.019}\right)^{exp(-0.773z_{t1}-0.599z_{t3}+0.768z_{t5}+0.317z_{t9}+0.585z_{t11})} \quad (11)$$

Table 2: Analytical test result evaluation of the suitability of the dump track data.

Risk factors	Pearson correlation coefficient	p-value of PH-assumption
Shift (Z_{t1})	-0.006	0.940
Fitness with loader (Z_{t3})	0.062	0.399
Road slope (Z_{t5})	-0.0005	0.945
Road situation (Z_{t9})	0.044	0.547
Carting distance (Z_{t11})	-0.096	0.190

Table 3: Estimation of risk factors of dump tracks using SPSS.

Variables in the relationship							
Step No.		**α**	**Standard error**	**Wald**	**Degree of freedom**	**p-value**	**Exp(α)**
Step 7	Z_1	-0.773	0.232	11.082	1	0.001	0.461
	Z_{t3}	-0.599	0.155	14.928	1	0	0.549
	Z_{t5}	0.768	0.109	49.234	1	0	2.155
	Z_{t9}	0.317	0.172	3.391	1	0.066	1.373
	Z_{t11}	0.585	0.178	10.839	1	0.001	1.794

3.2. A preventive maintenance program based on the dump track reliability

In this paper, the Ex-PHM model was used in order to insert the environmental conditions on the reliability, and integrate the imperfect maintenance. This model has the two parameters of a_j and b_j, whose values for the three basic modes, worse than the basic state, are better than the basic state (but not at the new level) in Table 1. Therefore, for the function of the system risk rate, without affecting the environmental conditions and considering the imperfect maintenance, Eq. (2) will be as follows:

$$\lambda_d\left(t+\sum_{j=1}^{n} T_j\right)=A_n\frac{1.354}{145.699}\left(\frac{t+b_n y_n}{145.699}\right)^{0.354} \quad (12)$$

Finally, the risk rate function consists of three elements of performance, environmental conditions, and imperfect maintenance, as follows:

$$\lambda_a\left(t+\sum_{j=1}^{n} T_j, z\right)=\left[A_n\frac{1.019}{29.512}\left(\frac{t+b_n y_n}{29.512}\right)^{0.019}\right] exp(-0.773z_{t1}-0.599z_{t3}+0.768z_{t5}+0.317z_{t9}+0.585z_{t11}) \quad (13)$$

If the actual values of a_j and b_j are placed, Eq. (13) changes as follows:

$$\lambda_a\left(t+\sum_{j=1}^{n} T_j, z\right)=\left[\prod_{j=1}^{n}\left(\frac{6j+1}{5j+1}\right)\frac{1.019}{29.512}\left(\frac{t+\left(\frac{n}{2n+1}\right)y_n}{29.512}\right)^{0.019}\right] exp(-0.773z_{t1}-0.599z_{t3}+0.768z_{t5}+0.317z_{t9}+0.585z_{t11}) \quad (14)$$

Therefore, according to the relationships above, four general strategies for reliable preventive maintenance can be proposed:

a. **The first strategy (b):** The preventive maintenance is perfect and ignores the environmental conditions ($\lambda_b(t)$ in Eq. (8)). The system returns to the GAN state after PM.
b. **The second strategy (c):** The preventive maintenance is perfect, and considers the risk factor effect ($\lambda_c(t)$ in Eq. (10)). The system returns to the GAN state after PM, and the environmental conditions affect the system's life.
c. **Third strategy (d):** The preventive maintenance is imperfect, and ignores the effect of risk factors ($\lambda_d(t)$ in Eq. (12)).
d. **Fourth strategy (a):** The preventive maintenance is imperfect, and considers the risk factor effect ($\lambda_a(t)$ in Eq. (13)).

It should be noted that the presented strategies are somehow the previous strategies completed form. Also although the proposed preventive maintenance type is in all the four time-based strategies, with this difference, the suggested maintenance intervals are constant in the two primary strategies for system or component life, and preventive maintenance is a periodic type. Still, two strategies, number three and four, preventive maintenance, are periodic but the proposed intervals will vary according to the effect of the maintenance in each period (cyclic). Table 5 and Figure 3, preventive maintenance for critical values of reliability for the third and fourth strategies for the two maintenances, are presented.

Table 4: Preventive maintenance intervals for different strategies for critical reliability values.

Strategy type	Number of maintenance activities	Critical reliability value per every preventive maintenance activity			
		90%	85%	80%	75%
T^a_{pm} (Hr) (Zi=1)	1st PM	2.422	3.707	5.06	6.493
	2nd PM	1.951	2.987	4.078	5.234
T^d_{pm} (Hr)	1st PM	28.784	38.265	48.36	58.341
	2nd PM	6.616	9.145	11.581	13.99

In these strategies, the values of all risk factors are considered one. As indicated above, the fourth strategy is reducing the second strategy so the proposed maintenance interval in the first activity of the maintenance from the fourth strategy is the same as the proposed interval for the entire life span in the second strategy. This is true for the third and the first strategies. According to the diagram depicted in Figure 3, the PM time intervals for the first activity in the fourth strategy for the levels of 75, 80, 85, and 90% reliability are, respectively, 6.493, 5.06, 3.707, and 2.422 hours, which is the same intervals as proposed by the second strategy.

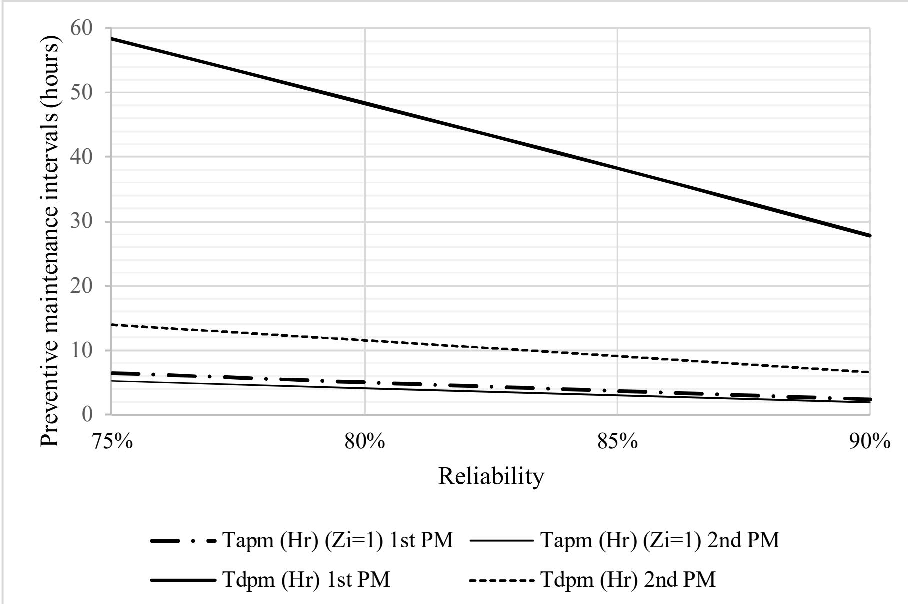

Figure 2: Preventive maintenance intervals for different strategies for critical reliability values.

In the second activity of this interval, the fourth strategy will drop to 5.234, 4.078, 2.987, and 1.951. The proposed intervals by the third strategy (and first for entire life) for the levels of 75, 80, 85, and 90% reliability are 58.341, 48.36, 38.265, and 27.784, respectively. In most engineering operations, 80% is used as the best operational value for performance evaluation and system performance. Table 6 lists the preventive maintenance intervals for four activities.

The above times indicate that the first preventive maintenance of the dump truck should be performed 5 h after the operation, and the second activity 4 h after the operation. The third and fourth activities should be performed at 3.5, and the next 3 h in order to ensure the system reliability with the fourth strategy and maintain a value of 1 for the risk factors at a level of 80%.

In order to determine the effect of the environmental conditions at the proposed timing of the two strategies (fourth and second), the preventive maintenance of these impacts is indicated in Table 7 and Figure 4; "carrier spacing" indicates the implementation times for the risk factor changes.

Table 5: Preventive maintenance runtimes for critical reliability of 80%.

PM strategy	Number of PM activities			
	1	2	3	4
T^{a}_{pm} (Hr) (R=%80)	5.06	4.078	3.459	1.92
T^{d}_{pm} (Hr) (R=%80)	48.36	11.581	10.254	9.035

Table 6: Preventive maintenance times in different environmental conditions.

T^{a}_{pm} (Hr) (R = 80%)		Number of PM activities			
Risk factor	Risk factor level	1	2	3	4
Shipping distance (Zt11)	Short shipping distance	6.772	5.458	4.63	3.91
	Normal shipping distance	3.814	3.074	2.608	2.202
	Long shipping distance	2.15	1.733	1.47	1.241

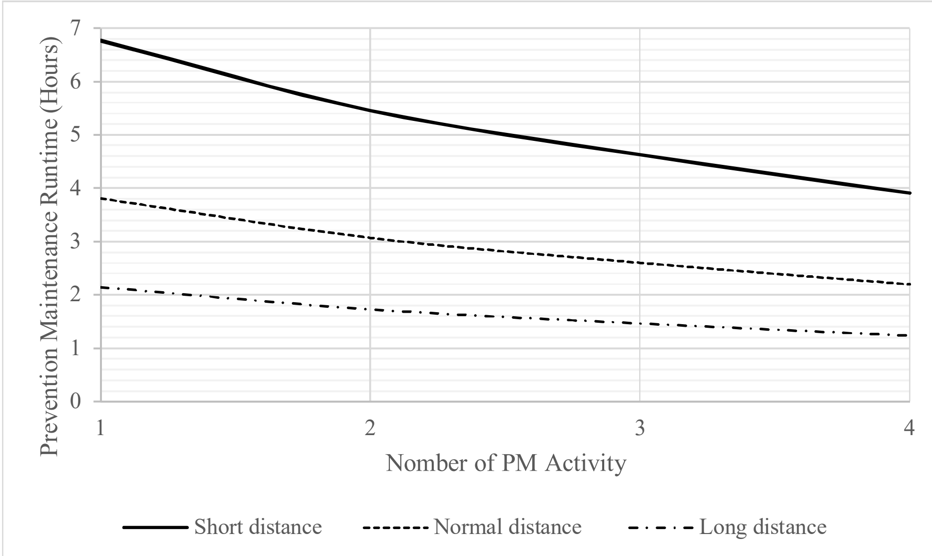

Figure 3: Preventive maintenance times in different environmental conditions.

The critical reliability value is 80%. As we observe, as the environmental conditions become harder by increasing the transport distance, the probability of failures increases and the intervals are shortened. In addition, after each PM, the system will drop and shorten the interval. In Table 8 and Figure 5, the PM intervals for different effects of the imperfect maintenance are calculated and drawn up for the critical reliability value of 80% for the three modes.

Table 7: Execution times of PM for various effects of imperfect maintenance.

T^{a}_{pm} (Hr) (R = 80%)		Number of maintenance activities			
Risk factor	**Effects of imperfect preventive**	**1**	**2**	**3**	**4**
Normal shipping distance	Worse than basic state	3.814	2.695	1.935	1.362
	Basic state	3.814	3.074	2.608	2.202
	Better than basic state	3.814	3.258	2.952	2.671

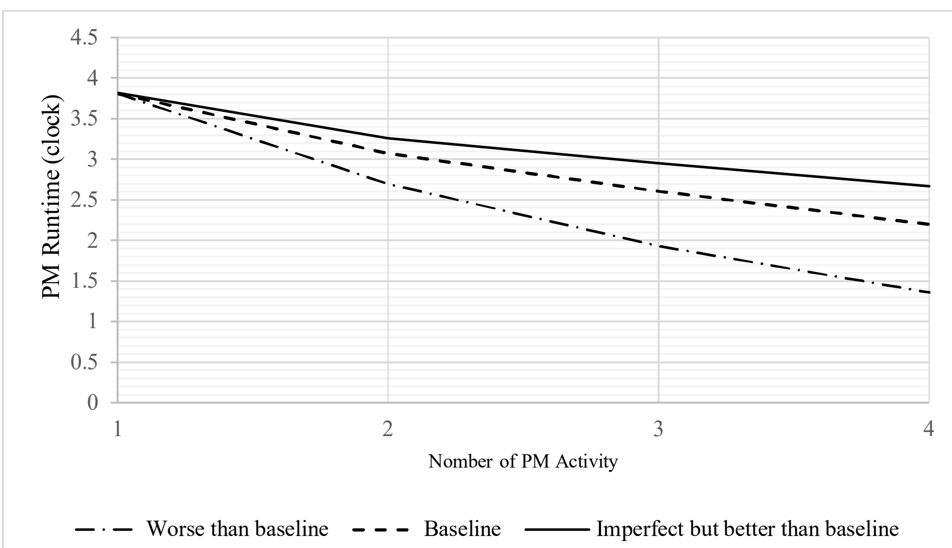

Figure 4: Execution times of PM for various effects of imperfect maintenance.

Clearly, with the system worsening after a net execution, the proposed intervals are shorter than the three modes.

4- Conclusions

In the first step of this section, a suitable timetable for implementing the preventive maintenance of the sub-system using the failure behavior and its environmental impact was presented. Then the effects of the maintenance performance from the perspective of the imperfect maintenance (the closest to the actual situation) were used in the studies, and the model became more complete. It is a combination of the environmental conditions and the effective performing maintenance on the proposed strategy or simply, a combination of poor preventive maintenance with good environmental conditions would be equal to perform a good preventive maintenance and poor environmental conditions. In this paper, maintaining the reliability of a truck sub-system, Komatsu HD785-5, at a confidence level of 80% was considered as the goal of the maintenance strategy. Ultimately, the proposed preventive maintenance intervals were "limited to reliability". The reliability analyses for this sub-system were performed in four reliability functions, and four types of preventive maintenance strategies were proposed. In the first strategy, no environmental condition and no effect of imperfect maintenance were included; in the second strategy, the effect of the environmental conditions was executed but the impact of the imperfect maintenance was ignored; the third strategy was proposed only based on the impact of the imperfect maintenance, and the impact of the environmental conditions was not considered; in the fourth strategy, which was the complete strategy, both the effects of the environmental conditions and the imperfect maintenance were taken into account. Then considering the reliability function for each strategy, the appropriate repair time was calculated. It should be noted that the proposed preventive maintenance interval in the first two strategies is the cyclic type that is always constant during the run. Still the intervals presented in the second and third strategies are of the periodic type, i.e. in each run, updates the proposed intervals based on the effects of the maintenance. The results of the analysis showed that the first preventive maintenance for the dump track 5 h after the operation, the second activity 4 h after the operation, and the third and fourth activities should be performed at 3.5 h and 3 h after activity in order to ensure the reliability of the system with the fourth strategy and per amount of 1 for the risk factors maintained at a level of 80%. The difference in the suggested intervals in this method reflects the effects of an imperfect maintenance. Regardless of that, the second strategy with a suggested time of 5 h would be executed. Regarding the impact of the environmental conditions on the net strategy, the analysis results showed that for different values for the "carrier distance" risk factor, different maintenances would be presented, which shows the undeniable environmental impact on the maintenance strategy. Also the analyses were repeated for the various effects of preventive maintenance in imperfect maintenance (basic state, worse than basic state, and better than the basic state). In this case, different ranges were obtained. In general, it can be said that in presenting a realistic preventive maintenance interval, a strategy must consist of three main elements: the system performance index (reliability), the impact of the environmental conditions (risk factors), and the effects of implementing the preventive maintenance (imperfect maintenance), i.e. a preventive maintenance strategy was provided for this kind of sub-system. Since this maintenance program was carefully obtained, the proposed approach could be considered as a basis for future decision-making for the other mineral systems.

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مدل نرخ مخاطرات توسعه‌یافته در نگهداری و تعمیرات پیش‌گیرانه

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ارسال ۲۰۲۱/۰۵/۰۸، پذیرش ۲۰۲۱/۰۷/۰۵

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چکیده:

موضوع نگهداری و تعمیرات (نت) در صنعت معدن‌کاری چه به صورت مستقیم در غالب هزینه و چه غیرمستقیم به شکل افت زمان و از دست دادن تولید خودی نشان داده و چشم پوشی از آن به معنی بهره‌وری کمتر از سرمایه و از دست دادن سود بیشتر است. در این مقاله نت مبتنی بر قابلیت اطمینان با بینشی متفاوت از قبل که آیا واقعا سیستم بعد از تعمیرات "به حالت نو برمی‌گرد" یا "به بدی قبل از تعمیرات باقی می‌ماند" مورد بررسی قرار گرفت. زیرا در شرایط واقعی نت سیستم را به حالتی بینابین شیفت می‌دهد. از سویی دیگر اجرای نت به طور بارزی متاثر از شرایط محیطی مانند سرد یا گرم بودن آب و هوا، میزان مهارت اکیپ تعمیرات، داخل یا خارج از تعمیرگاه بودن محل تعمیر،... می‌باشد که این شرایط موسوم به "فاکتورهای ریسک" هستند. از این رو تحلیل‌ها نیازمند مدلی است که قادر به پوشش دو پارامتر اساسی یعنی ۱) تاثیر ناقص بودن تعمیرات و ۲) تاثیر فاکتورهای ریسک باشد. مدل نرخ مخاطرات متناسب توسعه یافته یکی از رویکردهای آماری نوین برای حل این مسئله است که با ترکیبی از مدل نرخ مخاطرات متناسب و مدل هیبریدی ناقص به حل این مسئله می‌پردازد. محققین در این مقاله برای دستیابی به بهترین حالت چهار استراتژی مختلف نت پیشگرانه را در نظر گرفتند. تمامی این استراتژی‌ها مبتنی بر زمان بوده، با این تفاوت که بازه‌های نت پیشنهادی در دو استراتژی نخست ثابت بوده (ادواری) و در استراتژی سوم و چهارم نت پیشگیرانه از نوع پریودیک (هر بار متفاوت از قبل) است. در آخرین بخش نیز این استراتژی‌ها برای یک دستگاه دامپتراک کوماتسو HD785-5 از معدن مس سونگون مورد استفاده قراره گرفت. بازه‌های چهار نوبت اجرای نت پیشگیرانه برای دو استراتژی نخست در جهت دستیابی به قابلیت اطمینان ۸۰ درصد و با فرض مقادیر متوسط فاکتورهای ریسک به ترتیب ۴ و ۴۸ ساعت بود. این بازه‌ها برای استراتژی سوم به ترتیب ۴۸/۳۶، ۱۱/۵۸، ۱۰/۲۵ و ۹/۰۳۵ بدست آمده و برای استراتژی چهارم ۵/۰۶، ۴/۰۷۸، ۳/۴۵۹ و ۱/۹۲ محاسبه شد.

کلمات کلیدی: قابلیت اطمینان، نت، مدل نرخ مخاطرات متناسب توسعه یافته، مدل نرخ مخاطرات متناسب، مدل هیبریدی نگهداری و تعمیرات ناقص.