J. Appl. Environ. Biol. Sci., 5(7S)340-348, 2015

ISSN: 2090-4274
Journal of Applied Environmental and Biological Sciences
www.textroad.com

Power Law Model for Reliability Analysis of Crusher System in Khoy Cement Factory

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Received: March 19, 2015
Accepted: May 2, 2015

ABSTRACT

The first step of the cement making process is crushed limestone by crusher system. The performance of this system is affected by maintenance, the operating environment, efficiency, the operation process, the technical expertise, transporting material, distance, failures and etc. On the other hand, according to high costs of keeping these systems in operational mode and existence of complex connections between different subsystems, carrying out proper maintenance become more and more important. The purpose of this paper is to discuss operational and maintenance challenges by assessing system reliability. The required data (time between failures (TBF)) for statistical analysis were collected and sorted in chronological order from two main data sources that consisted of daily operation and production reports and maintenance reports for 18-month periods. Then, reliability-based maintenance was considered to achieve the 90% level of reliability performance. Based on this critical level, 47.25 hours are suggested as PM intervals. Analysis of the effect of this strategy indicated 1.6 times improving efficiency of the fixed capital.
KEYWORDS: Crusher system, Maintenance, Reliability, Time between failures, Power law model.

1. INTRODUCTION

One of the most important and inseparable stages of mineral processing in various fields and industries is crushing materials. This subject, like cement which is one of the largest industries of the world consists of different departments (crushing plant, raw material mill, kiln and firing (Clinkerization), cement mill, packing plant) and also complex systems, which obtains much importance [1], [2]. Crushing occurs at the begging of the cement making process in the crusher system. The performance of this system is affected by operating environment, maintenance performance, transporting material, distance, failures and etc. On the other hand, according to the high cost and necessity of connection with operation cycle, proper operation and maintenance of these systems become more essential. Therefore, in this paper reliability, as one of the operational indicators of system for assessing crusher system, was considered for a crushing plant in Azarabadegan Khoy cement factory. Application of reliability in the mining industry has grown slowly. However, some companies have implemented it quite successfully. Examples include the Hammersley Iron open pit mine in Australia [3] and the Iron Ore Company of Canada [4], [5]. Since this method provides a structured methodology for arriving at the correct balance between breakdown maintenance, planned interval repair, and repair on condition, it is an attractive technique for mining companies striving to optimize their maintenance process. In terms of distribution fitting to failure and repair data, Kumar has done extensive study [6], [7].
Therefore, in this paper after assessing the failure pattern, in order to preserve reliability in a certain level and its improvement, the proper preventive maintenance interval was proposed.

2. Analysis theory and definitions

2.1. Reliability

Reliability is defined, as the probability of doing an activity through components, items, products or systems that have been designed for it, in defining environments, fixed time intervals and without failure on it. In terms of statistical vision, reliability function is denoted by equation (1) **[8], [9]**:

$$R(t) = P(T > t) = 1 - P(T \le t) = 1 - F(t) = 1 - \int_0^t f(x)dx \qquad (1)$$

In this equation R(t) is reliability function, P is probability function and F(t) is cumulative failure distribution function. Reliability and availability analysis are generally done with the assumption that time between failures (TBFs)

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contains independent and identically distributed (i.i.d). In this case study, further reordering of (TBFs) on the basis of their amount is corrected for fitting suitable distribution from various distributions in order to show TBFs behavior. This process is known as Renewal process (RP). However, before analyzing the data, trend test and serial correlation test should be done to determine the correctness of iid assumption. If the (i.i.d) assumption is rejected, classical statistical methods for reliability analysis will be unsuitable. Therefore, a nonstationary model like "non- homogeneous Poisson process" should be used for the analysis. Fitting an NHPP for nonstationary data is different from fitting distribution of i.i.d data. NHHP is a functional form that has been most commonly applied to repairable systems and is based on the power low process **[10]–[14]**.

2.2. Failure Rate

Finkelstein defines failure rate as the probability (risk) of failure in an infinitesimal unit interval of time [15], whose function is shown as equation (2):

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)} \tag{2}$$

Where λ: is failure rate [8]. In general, failure rate is considered increasingly (wear-out phase), decreasingly (burn-in phase or primary difficulties occurred stage) and constant (useful life phase or ordinary operation stage) [16], [17]. In this paper, failure rate function and graphical method "Event plot" are used to determine the failure behavior of crusher systems and suggesting appropriate maintenance strategies.

2.3. Power Law Process

In more complicated systems like automobiles, communicating systems, printers, pharmacy systems, helicopters, locomotives, trains etc…, generally, repair was done at the time of failure occurrence instead of repairmen. While these systems are studied in the form of case and field, and according to the environment (al) conditions, using distributions like Weibull is not usually possible. Therefore, in this case study in order to study the reliability features of complex repairable systems, this process will be used instead of distribution. One of the favorable process in this field is PLP model. This model is popular for some reasons [18]:

- Because of having a good scientific basis in the field of "minimal repair". In this condition, only the repair is capable to burn the system into active condition.
- If the time follows up to the first failure occurrence of the Weibull distribution, minimal repair will be controlled with PLP model after failure occurrence.
- PLP model generalized of Poisson process obtains basis of distribution. Besides, this model usually is comprehensible on management approach and therefore, deduction of results is easier.

Crow introduced this model in 1974 for multi-form systems, and it has been developed in 1979, 1990, 1993, 2003 by him. It should be mentioned that a distribution is considered for “single failure" since distribution theory would not have applied on the failures of complex systems. In fact, TBFs of complex systems would not follow fitted distribution for an item. Therefore, distribution of items is used with single failure and would not be applicable for equipment on system level [18]. For most systems in real world repairing in order to restore the system to active state would be sufficient. If in water pump a washer failure, the only repair is the replacement of that washer with a new one and other repair is unnecessary, which forms the “minimal repair” concept. Under this concept, failure rate after repair is the same failure rate as before the failure [19]. In this study, frequency of failures in system level will follow the NHPP if the first failure follows the Weibull distribution system whose failure rate is given by equation (3).

$$r(t; \theta, \beta) = \left(\frac{\beta}{\theta}\right)\left(\frac{t}{\theta}\right)^{\beta-1} \tag{3}$$

Under the minimal repair concept, its failure rate and reliability are presented by equations (4) and (5) [11], [12], [18]:

$$\lambda(t; \theta, \beta) = \left(\frac{\beta}{\theta}\right)\left(\frac{t}{\theta}\right)^{\beta-1} \tag{4}$$

$$R(t; \theta, \beta) = \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{5}$$

Therefore, this case presented PLP, where θ and β are scale and shape parameters and (t) is the running time. When [16]:

- $0<\beta<1$, failure rate of machine decreases as the machine age increases.
- $\beta=1$, failure rate is constant and the above model is transforming to HPP model.
- $\beta>1$, failure rate increase with increasing time (t) and system is to gain in degradation.

θ and β parameters can be calculated through equations (6) and (7) [12]:

$$\hat{\beta} = \frac{n}{\sum_{i=1}^{n-1} ln\left(\frac{t_n}{t_i}\right)} \qquad \hat{\theta} = \frac{t_n}{n^{\frac{1}{\beta}}} \tag{6}$$

$$\hat{\beta} = \frac{n}{\sum_{i=1}^{n-1} ln\left(\frac{t_n}{t_i}\right)} \qquad \hat{\theta} = \frac{t_n}{n^{\frac{1}{\beta}}} \tag{7}$$

Where ti; is total time up to i'th event, n; is number of failure events. Equation (6) is used when the test has”failure-truncated”. In addition, equation (7) is used for “time-truncation”.

Graphical method based on mean cumulative function with confidence band of 95 percent is utilizable for goodness of fit test of parameters estimation in PLP model which is presented in equation (8) [12]:

$$\mu(T;\beta,\theta) = E(N(T)) = \left(\frac{T}{\theta}\right)^{\beta} \quad (8)$$

2.4. Preventive Maintenance

Maintenance can be defined as the required activity for equipment preservation in active condition and work continuation with main production capacity. STD – MTL defines it as below:

"Actions which have fulfilled to ensure whether equipment, system or component functions are available until the next scheduled maintenance" [20].

Maintenance strategies are divided based on two general categories [19]:

- corrective maintenance(CM)
- Preventive maintenance (PM)

The aim of CM is to restore the system when it fails and the aim of PM is to retain or restore the system into active state when it is operating [19].

While the system is in wear-out phase (increasing failure rate), four different policies are suggested to decrease the failure rate. These consist of: De-rating, PM, Component replacement and technology improvement. Among these suggested strategies, PM is the most applicable of them due to its output and operational features [11], [16].

"Reliability based maintenance" strategy is a kind of time-based preventive maintenance, in which a critical level of reliability can be defined for the system and be based on this critical level PM interval can be suggested. Using this method brings about failure distinction on inspection and makes it possible to perform every kind of PM on distinguished failures [11].

One of the significant PM aims is improving system reliability so that the results of reliability improvement can be observed exactly after the first performance of PM [11], [21].

Reliability function after PM performance which is shown as RPM(t)can be calculated by the following equation(9) [11]:

$$R_{PM(t)} = \begin{cases} R(t) & 0 < t < T_{PM} \\ R^{n}(T_{PM})R(t - nT_{PM}) & nT_{PM} \le t < (n+1)T_{PM}, \quad n \ge 1 \end{cases} \quad (9)$$

In this equation, TPM, PMs intervals and n is the number of maintenance activities which have already been performed.

3. Case study

Here we present a case study describing the reliability analysis of the crusher subsystem in Azarabadegan Khoy cement factory (crushing department in Iran). The impact crusher (84×135MB) with 1000-1200 ton capacity is used to reduce the size of ore in mineral processing plant. A schematic diagram of crushing department is shown in Fig 1. The ore is hauled to the crushing department by truck from the mine. This department was assumed to comprise three clearly identifiable subsystems; Apron feeder, Crusher and Screen. As was noted earlier in this article was focused on crusher subsystems for the purpose of reliability analysis. The output of this phase is moved to the mixing bed hall by conveyors.

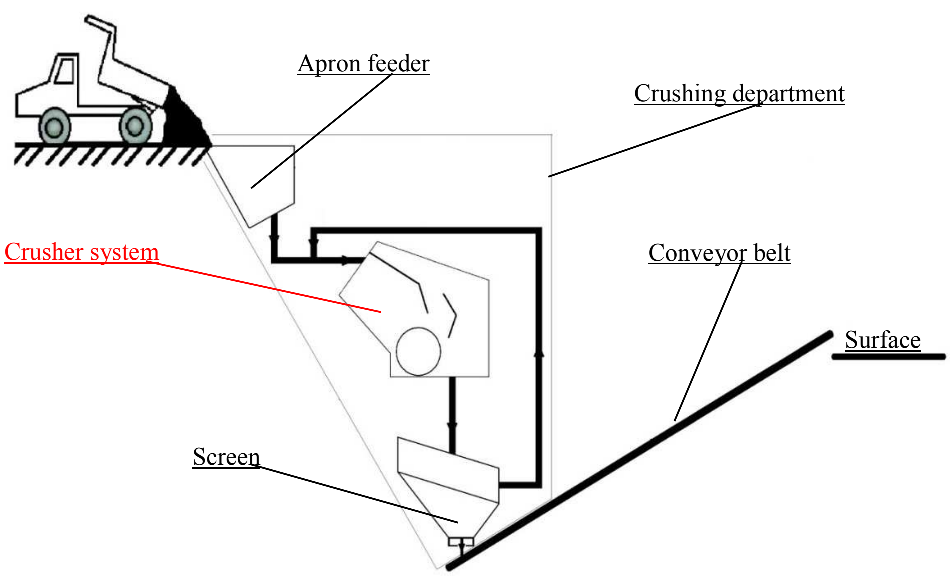
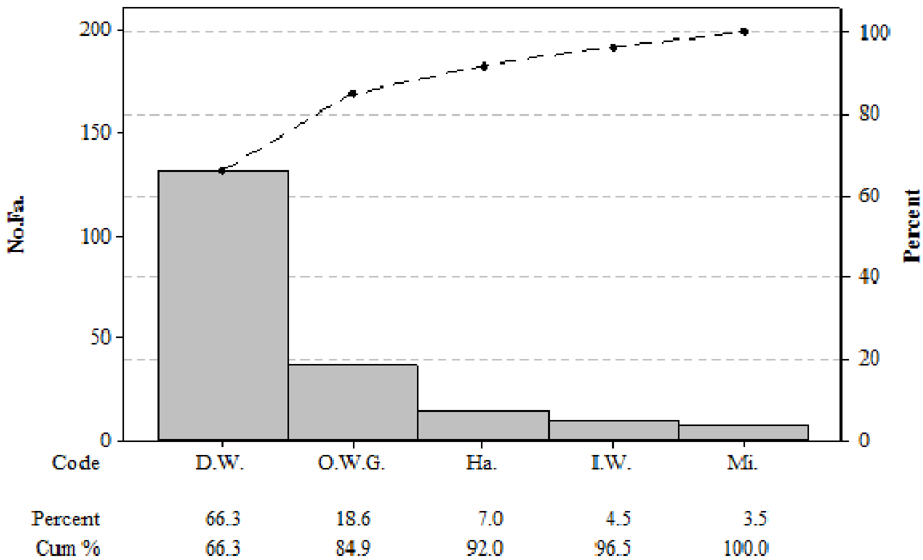


Fig 1. Schematic diagram of crushing plant

3.1. Data Collection and Analysis

In order to carry out the analysis the required data of equipment operation should be collected. The failure data in this research, such as the failure occurrence times and failure reasons were collected from two main data sources that consist of daily operation and maintenance reports for a 18-month period. In addition, the time of failures (TBFs) was calculated. Then, Pareto method was used to analyze the frequency of TBFs. Minitab 16 software also was used in ongoing analysis.

Due to the provided reports, six main failures efficient on this system were identified and the frequency analysis was accomplished after coding these failures.



Disks Welding (**D.W.**), Other Welding & Griding (**O.W.G.**), Hammer (**Ha**.), Impact wall (**I.W.**), Miscellaneous (**Mi.**)

Fig 2. Pareto chart of Crusher system

Fig **2**, shows the recollecting the analysis for collected TBFs. In this figure, the upper column demonstrates percent and the failure number in each type of failures, and the broken line above the columns demonstrates the cumulative percentage of failure frequency.

As it is observed, D.W. failure 66.3 percent has the highest frequency and O.W.G. and Ha. Failures with 18.6 and 7.0 percent settled at subsequent ranks. The frequency of the most occurred failure is high and must be analysed.

3.2. Independence and identical distribution tests

As it was mentioned, in order to analyze i.i.d assumption of the data, trend and serial correlation tests were used. In this article, to conduct trend test, both analytic (Laplace, MLI-Hdbk-189) and graphical (Total Time on Test) methods were used. In addition, in serial correlation test, graphical autocorrelation function method was used [12], [13].

The results of the analytic method of the trend test under the null hypothesis of "no trend" at $\alpha = 0.05$ level of significance is presented in Table 1. As it can be observed, P-values of TBFs are less than α, consequently the null hypothesis was rejected .

Table 1. Analytical trend test results

Crusher system	**Test**	
	MIL-Hdbk-189	**Laplace**
Test Statistic	294.8	2.15
P-Value	0	0.031
Test result	Monotonic Trend	Deteriorating Trend

The graphical trend test is shown in

Fig **3**. This graph shows complete conformity to the results of the analytic tests. Decisions about the acceptance or rejection of the null hypothesis of "no-autocorrelation" by the autocorrelation function (ACF) at 95% of confidence level, were made by using autocorrelogarms (Fig 4). In this graph ACF values are represented by columns and 95 percent confidence bounds are represented by upper and lower dashes. As it can be seen, AFC column on time lag one of system is 0.017 and is placed in the confidence level. Therefore, the null-hypothesis is accepted .

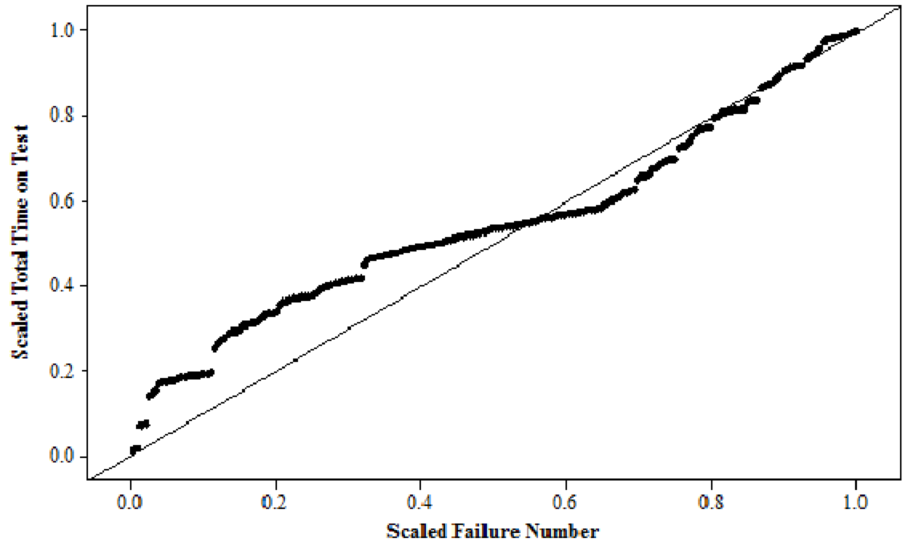


Fig 3. Graphical trend test for crusher system

Giving attention to trend and serial correlation tests, the assumption that the data sets are i.i.d in time is not contradicted for TBF data of the crushing subsystem assumption and therefore NHPP method will be suitable for the description of failures behavior in running time. As it was pointed, in this research PLP method which is a special variety of NHPP was used to analyze the reliability of the subsystem.

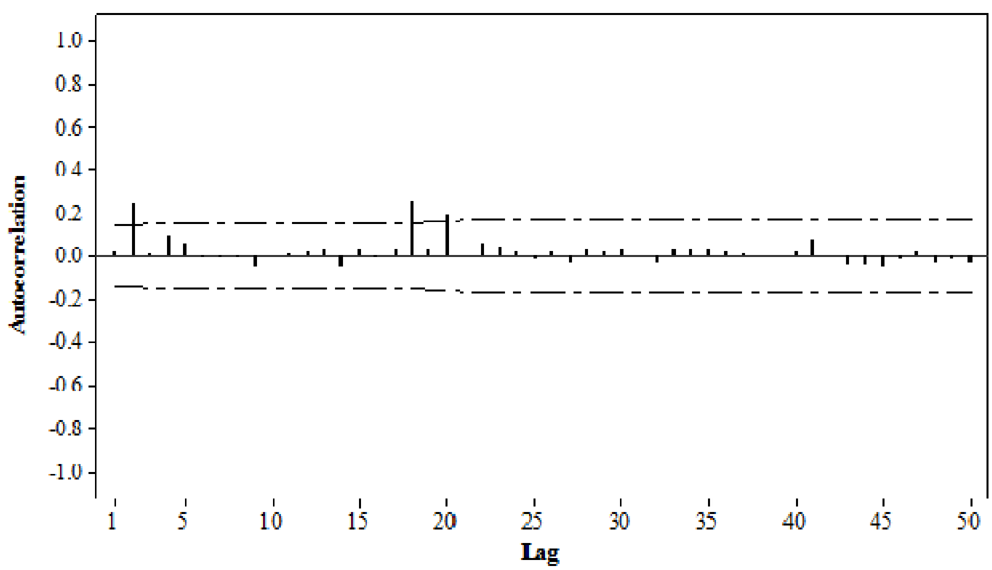


Fig 4. Autocorrelogram of different lag for crusher system

3.3. Reliability and Failure Rate

After selecting the PLP method to describe system TBFS behavior, parameters of the model (scale (θ) and shape (β)) in 95% confidence bounds were calculated as shown in Table 2.

Table 2. Parameter estimation of crusher system

		95% Normal Confidence Interval(CI)		
Parameter	**estimation**	**Standard Error(SE)**	**Lower**	**Upper**
Shape	1.350	0.095	1.17533	1.55074
Scale	250.19	70.629	143.871	435.077

After estimating model parameters from a graphical method based on mean cumulative function (MCF) (relation (8)), with 95% confidence bounds for goodness of fit, PLP model was used according to Fig 5. As it is presented, PLP model and estimated parameters are capable of describing system failure behavior.

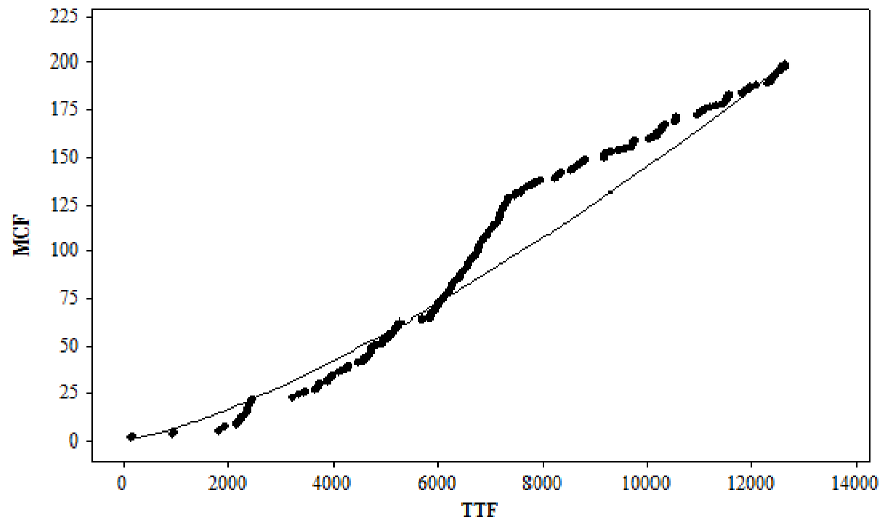


Fig 5. Goodness of fit test for crusher system

Due to estimated parameters, reliability was calculated by utilizing equation (5) and its graph (plot) for the time period 1000 hours. The result is shown in Figure (6).

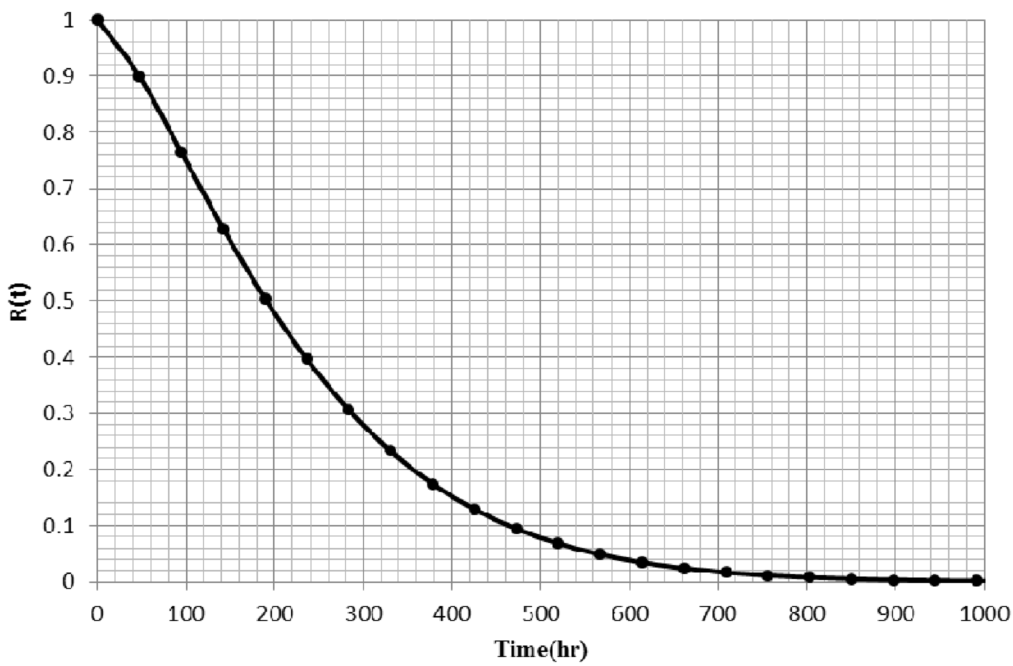


Fig 6. Reliability of crusher system

As it can be observed, reliability of crusher subsystem without using maintenance, nearly after 800 hours of operation will reach zero. Decreased rate at the beginning period is very intensive and the system will fall to 50% of reliability after 190 hours of operation. In such a situation, after 460 hour system operation, the probability of failure occurrence will be 90%, and after 50 h there is 90 % probability of operation without failure occurrence in the system.

The failure rate of the system was also calculated via equation (4) and its plot is traced on Fig 7 at 2500 h of operation time. To consider the estimated shape parameter ($\beta>1$), the crusher is increasing failure rate (IFR) (placed at wear-out phase) and in case the maintenance activities are not performed suitably, failures cause serious accidents (events) in the system and will severely decrease the reliability.

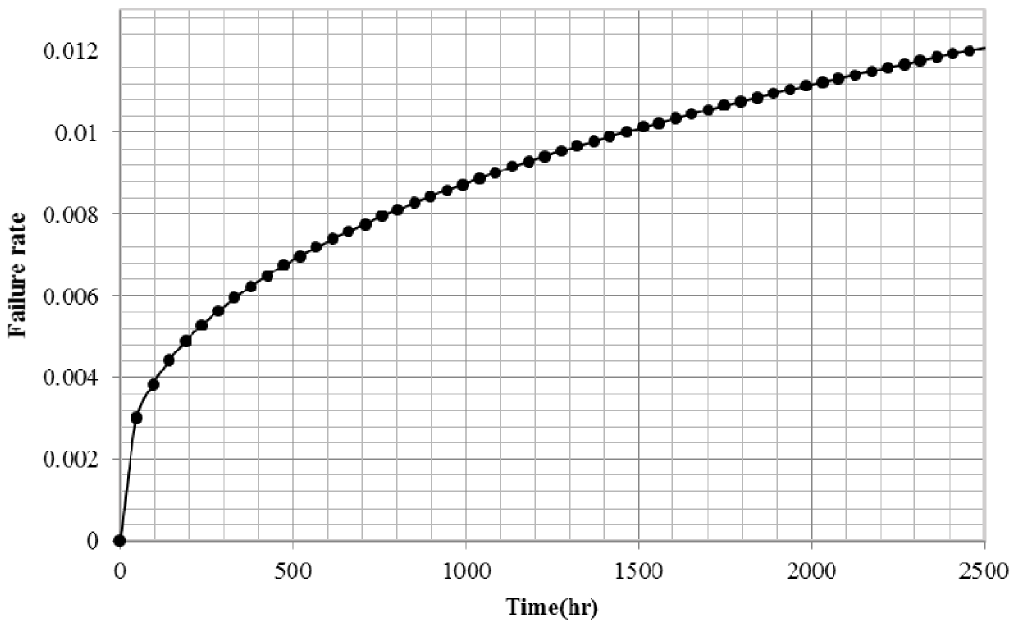


Fig 7. Failure rate of crusher system

In Fig 8 and Fig 9 event plot of the system and various kinds of failure have been traced. In this plot, there is an increase in the frequency of D.W. and O.W.G with the passage of time. In addition, there is an increase in failures focus at the end of time intervals (multiple remark on time lines) becomes more evident at the end of the time period, consequently frequency of failures in the whole system has increased and the system in a degradation. The same results were obtained using the event plot and the shape parameter of PLP in the failure rate analysis.

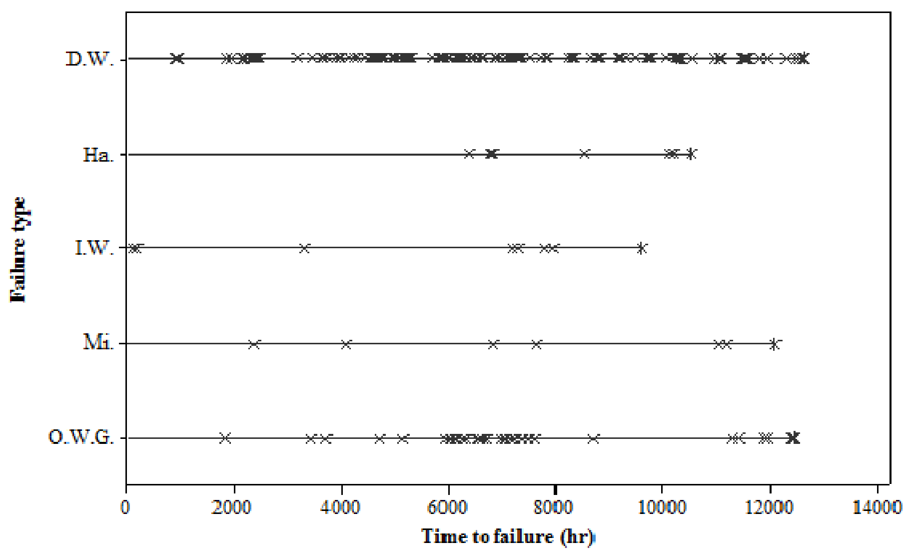


Fig 8. Event plot for failure types

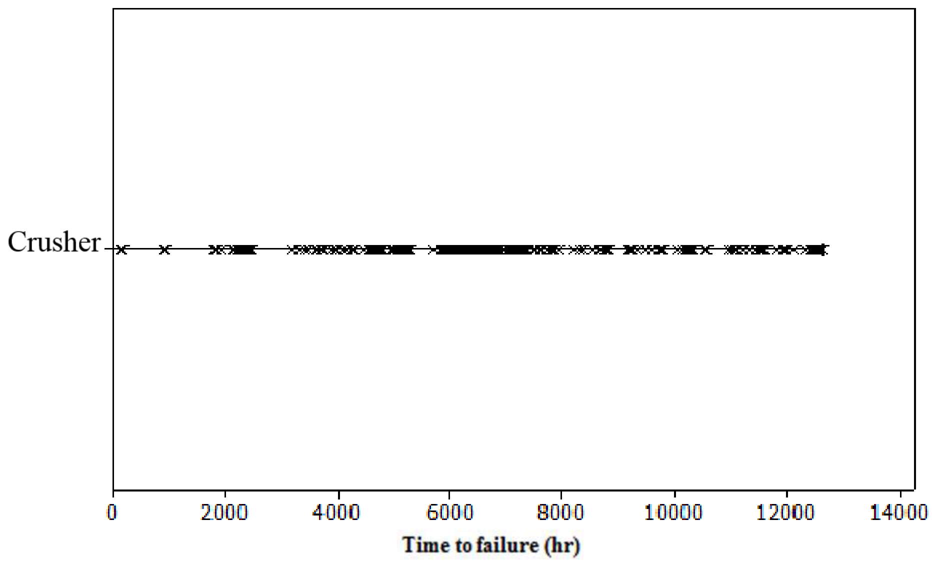


Fig 9. Event plot for crusher system

3.4. Maintenance intervals and reliability improvement

In systems with increasing failure rate, in order to prevent from wear-out, possible failures (which are not detectable during ordinary operations) should be detected and repaired. Additionally, preventive maintenance should be carried out. As it is indicated, in this research, preventive maintenance approach based on reliability was used.

According to the traced plot in Fig 6, reliability-based PM time intervals for 90, 80 and 70 percent levels of reliability are 47.25, 82.37 and 116.58 hours respectively. In the most engineering operations, 80% reliability is utilized as the best operational level for accessing operation and system efficiency. However, in this case (cement factory) because of the importance of operational connection and complexity, 90% reliability was considered as the target reliability level for maintenance activities. Therefore, to achieve 90% reliability for crusher subsystem, maintenance must be carried out before 47.25 hours, because after the machine has run for 47.25 hours without the failure, there is only 90% probability that it will not fail.

One of the important preventive maintenance aims is improving system reliability. Effect of PM on crusher reliability has been calculated based on equation (9) and is shown in Fig 10. Also, improvement of reliability (EF) is represented by secondary axis. The peak of the plot is at 410 hours and the subject can be described with due attention to change in failure rate at the beginning of running time. Furthermore, there is a sharp increase in failure and a gradual decrease up to 410 hours. After that there is a continuous increase.

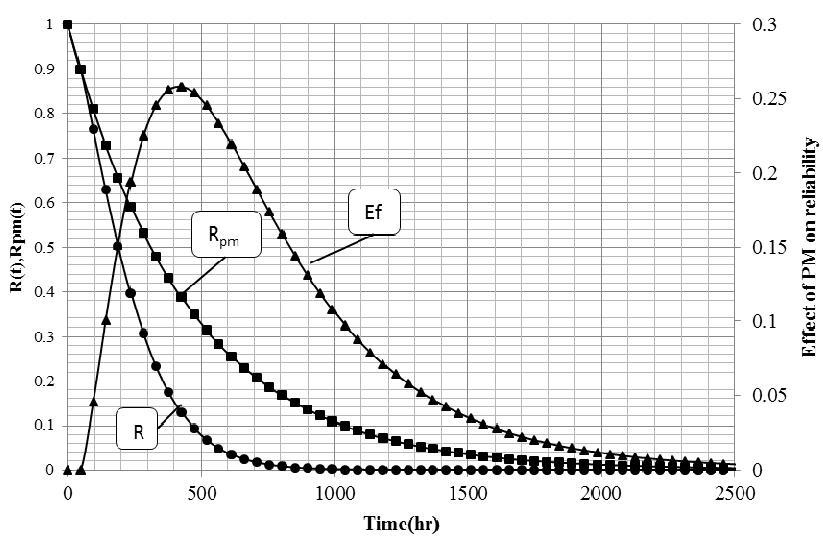


Fig 10. PM effect on reliability of crusher system

Based on Fig 10, the result of performing PM, becomes manifest exactly after the first maintenance or preventive service. Reliability of the system has increased from zero to 17% after 800 hours. Its value also becomes nearly zero after

2080 hours. In fact performing maintenance, improved the reliability period of the subsystem up to 1280 h. In other words, for the same capital cost the productivity of the machine increases about 1.6 times. Finally, all the above-mentioned strategies and changes will reduce the production cost.

4. Conclusions

In this paper the reliability of the crusher subsystem of the Azarabadegan Khoy cement factory was studied. The results of analytical and graphical trend and autocorrelation tests reject the independent and identically distributed (i.i.d) assumption for TBF data. Consequently, power low process which is a special form of the non-homogeneous Poisson process was utilized for failure behavior description. After estimating process parameters (shape and scale parameter) graphical goodness of fit test determined the suitability of PLP to describe the failure behavior. Evaluation of failure rate, shape parameter and the system event plot shows the degradation of the system state and its urgent need for preventive maintenance performing. Maintenance performing improved system reliability period from 800 hours up to 2080 hours as well as improving the productivity of capital cast 1.6 times.

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