Failure rate analysis of Jaw Crusher: a case study

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Abstract. Failure of crusher components has considerable influence on the productivity of a crushing plant. In order to improve performance and operational reliability, its critical components are needed to be identified to make replacement in time before any catastrophic failure happens. Though traditional maintenance practices exist in crushing plants, a methodical analysis of failure trend is imperative to improve operational reliability of this critical equipment. The present paper deals with failure analysis of rock crusher and its critical components using total time on test (TTT)-plot and other statistical tools. TTT-plot has proven to be a useful tool in reliability analysis.

Keywords. Total time on test; Jaw Crusher; time between failures; life data analysis.

1. Introduction

Maintenance and operational reliability are considered as important issues for un-interrupted plant equipment operation. The sudden and frequent failure of equipment components will lead to production loss. This becomes more critical for modern plant equipment in which plant owner have invested a major share of their capital investment. These machines demand correct, precision and time driven maintenance. Maintenance to be scheduled in time but becomes impossible without a methodical study on the trend of failure of the equipment and its components. Operational reliability investigation is desirable for reducing the maintenance cost of the plant equipment. The present study has examined failures of jaw crusher and its components in a major mineral processing plant. The failure data of two year duration are recorded from the plant maintenance register for analysis purpose. Maintenance and operational reliability using TTT-plotting has been already carried out for a fleet of diesel operated load haul dump (LHD) machines in a Swedish mine [1]. The same concept with additional statistical treatments has been considered here. Analytical methods such as Life Data Analysis (LDA) test and Maximum Likelihood (ML) estimation are also considered in this study. Failure data are examined through different statistical distributions. Their parameters are estimated using ML (maximum likelihood) method [2, 3]. ML estimation is used at confidence level of 90%. Confidence bounds can be expressed as two-sided or one-

sided. Two-sided bounds are used to indicate that the quantity of interest is contained within the bounds with a specific confidence. The graphical TTT-plot is used to examine increasing or decreasing trend of failure rates of components and the results are compared with the findings by ML method. Graphical techniques are used to test the independence and identical distribution (iid) of the data. LDA test is used for goodness of fit of the data for different distributions. The 2-Parameter Weibull distribution density function is given by the following equation.

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \quad \beta > 0, \eta > 0 \quad (1)$$

In Weibull plot, the parameter β describes the Weibull slope or shape parameter, i.e., The failure rate and change of failure rate (increasing or decreasing). The η is scale parameter which indicates the mean time between failures (MTBF). The primary advantage of Weibull distribution is the ability to provide reasonably accurate analysis with extremely small data size.

1.1 The mineral processing plant layout

A mineral processing plant circuit consisting of different operating units is shown in figure 1. In the circuit there is no stand by equipment. So, if one particular unit in the circuit is down, the whole operation stops, causing production loss of the plant. Maintenance of the units in time to improve operational reliability thus becomes essential.

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Figure 1. Block diagram of operational units.

Figure 2. A double toggle jaw crusher.

1.2 The jaw crusher

Crushing is the first stage of size reduction of mined rocks. Primary crushers are heavy-duty machines, used to reduce the run-of-mine (ROM) ore down to a size suitable for easy handling. A line diagram of a double toggle jaw crusher and its main components is shown in figure 2. The jaws are set at an angle to each other. The moving jaw moves gradually forward towards the fixed jaw causing fragmentation of rocks trapped inside the crushing chamber and then moves backward in the next half of its working cycle. The crushed materials get discharged from the bottom of the crusher during the return stroke by gravity.

Table 1. TBFs of the crusher and their components.

System/subsystem	No. of failures	Time between failure (hours)
Jaw crusher	40	250, 370, 380, 396, 273, 300, 324, 135, 165, 180, 405, 410, 420, 185, 200, 216, 108, 110, 132, 360, 360, 360, 60, 70, 431, 432, 432, 330, 340, 350, 360, 425, 430, 430, 360, 365, 400, 225, 245, 12
Back toggle	11	396, 600, 650, 711, 767, 1800, 455, 567, 800, 790, 800
Liner plate	10	888, 500, 560, 636, 670, 730, 600, 610, 620, 492
Jaw plate	9	60, 100, 810, 1100, 1248, 210, 400, 556, 708
Tie rod	10	708, 950, 1100, 790, 810, 828, 720, 750, 900, 1320

1.3 The concept and data analysis technique

This work analyzes failure rates of crusher and its components using LDA method, ML method and TTT-plots. The ML method needs application of software for solving mathematical equations. The TTT-plotting does not need structured data set. The method assumes that TBFs are independently and identically distributed (iid). To establish validity of this assumption, statistical tests are performed to examine the presence of structure or trend in the data.

Figure 3. TTT-plots at different failure rates.

Figure 4. Plots confirming identical trend of data for (a) Jaw crusher unit, (b) Liner plate, (c) Tie rod, (d) Jaw plate and (e) Back toggle.

1.4 Data collection and treatment of data

The failure data of two year duration are collected from the plant maintenance record book. The components of crusher which are critical and having major impact on plant's operation have been considered for analysis. TBFs of these components are presented in table 1. The unit of the TBF is hours. TBFs obtained due to stoppage of routine maintenance are classified as censored data. When a major breakdown occurred, the jaw crusher itself was considered as a component.

2. Methodology

2.1 TTT-plot

TTT-statistics were first used by Epstein *et al* [4]. In the last decade, different generalizations of this concept have been studied and applied to different areas of reliability [5]. The TTT-plot is used to analyze the trend of equipment failures. The plots help in formulating a suitable mathematical model from failure data and provide information about failure rate. Also, inconsistent

Figure 5. Plots confirming independence of data for (a) Jaw crusher unit, (b) Liner plate, (c) Tie rod, (d) Jaw plate and (e) Back toggle.

and incomplete data can be analyzed by this method [6–8].

In this study, TTT-plot is used to analyze rate of failures of crusher and its components considering time between successive failures (TBFs). Since this is often not the case for components of mechanical equipment like crushers, a graphical plot is found to be more informative. TTT-plots are indicative of the components increase or decrease in failure rates. It is used to determine the failure rate and to

schedule maintenance of ageing components [9, 10]. To develop a TTT-plot, following steps were considered:

- Time between failures (TBF) is structured as $0 \leq t_0 \leq t_1 \leq t_2 \leq \dots \leq t_n$
- S_i is determined from $S_i = nt_1 + (n-1)(t_2 - t_1) + \dots + (n-i+1)(t_{(i)} - t_{(i-1)})$
- X co-ordinate, (i/n)
- Y co-ordinate, $U_i = S_{(i)}/S_{(n)}$

Table 2. Result of Analysis with LDA Test.

System/subsystem	LDA statistic						Best fit model
	Exponential	Normal	Lognormal	Gamma	Weibull	Logistic	
Jaw crusher	43.98	1.08	1.28	3.83	0.33	6.53	Weibull
Liner plate	8.52×10^{-8}	0.010	1.73×10^{-5}	1.34×10^{-9}	1.0×10^{-10}	0.012	Weibull
Tie rod	5.36×10^{-8}	2.34×10^{-7}	7.0×10^{-7}	1.0×10^{-10}	1.0×10^{-10}	5.79×10^{-6}	Weibull
Jaw plate	1.0×10^{-10}	3.03×10^{-7}	5.5×10^{-9}	4.42×10^{-8}	1.0×10^{-10}	2.45×10^{-7}	Weibull
Back toggle	1.2×10^{-10}	3.91×10^{-8}	1.2×10^{-10}	2.24×10^{-7}	1.0×10^{-10}	1.15×10^{-8}	Weibull

Table 3. Maximum likelihood estimation of the Weibull parameter.

System/subsystem	β	η
Jaw crusher	1.17	290
Liner plate	4.33	631
Tie rod	3.18	888
Jaw plate	0.62	788
Back toggle	1.28	757

Where,

$i = i_{th}$ number of successive failure ($i = 1, 2, 3 \dots n$)

n = number of successive failures and total 40 successive failures have been considered in this study

S_i = total time on test at i_{th} successive failure

S_n = total time on test at all successive failures under study and is equal to 11738 in this case

The values i/n and U_i will lie between 0 and 1. The graphic representation of TTT is formed by plotting i/n on the horizontal axis and U_i on the vertical axis. In general, the plot of the scaled time-on-test transform is within a unit square. The plotted points are connected by straight lines. For an exponential distribution, the TTT-plot is close to the diagonal of a square unit. The departure of the plot from the diagonal indicates the behavior of the failure rate. The TTT-plot runs along and nearly coincides with the diagonal of the square in case of constant failure rate. When the TTT plot concaves downward, it suggests increase in failure rate, that is, the condition of unit or the machine as a whole is deteriorating in terms of failure. If the plot concaves upward, it would suggest that failure rate is decreasing, that is, the condition of individual unit or the total machine is improving and figure 3 explains such situations [11–13]. TTT-plot helps in obtaining the shape of the failure rate function which indicates failure rate and aging of components and decides most favorable time for preventive maintenance.

2.2 Trend analysis of failure data

To explore the presence of trend in the time between Failures (TBFs) data of jaw crushers and its components,

the cumulative time between successive failures are plotted against cumulative number of failures. To test the TBFs for independence, the failure data are tested for serial correlation. To test the data for serial correlation, the TBF are plotted $(i-1)_{th}$ against the i_{th} TBF data of jaw crushers and its components.

For identical test of data, the analysis is carried out using cumulative number of failure data and cumulative time between successive failure data. Corresponding plots are shown in figure 4 in which the data show a trend which confirms that they are identical.

For independence test of data, scatter plots are drawn between dependent and independent variables. The independent variable is the measured or recorded data whilst the dependent variable is the outcome. In independence test, the measured or independent variables are plotted in vertical axis. In this study, the $(i-1)_{th}$ TBF is a measured variable whereas i_{th} TBF. Corresponding plots are shown in figure 5 in which the data show no correlation and thus they are independent.

2.3 Nature of distribution and parameter estimation

Tests have shown absence of any distinct relationship among the failure data, thus iid assumption for the data set is not violated. To examine the nature of distribution of TBF data, Exponential, Weibull and Lognormal distributions are examined. The parameters of these three distributions are estimated by ML method using WEIBULL++ software. Life Data Analysis (LDA) test is used as a measure of goodness-of-fit of different distributions [14]. The result of the analysis is shown in table 2.

The TBF data of the crusher and its components revealed that 2 parameter Weibull distributions is the best-fit model for describing the data. The parameters of the Weibull distribution are estimated by ML estimation. The details are presented in table 3. The shape and scale parameter values of Weibull distribution are determined using ML estimation method. Where β is shape parameter which is also known as the Weibull slope, η is scale parameter which indicates the mean time between failures (MTBF) and t is time failed which indicates the mean time to failure (MTTF) of a

Figure 6. TTT-Plot of (a) Jaw crusher, (b) Liner plate, (c) Tie rod, (d) Jaw plate and (e) Back toggle.

component. The value of scale parameters (η) are used to determine failure rates.

In ML estimation, the shape parameter value below 1 indicates decreasing nature of failure rates. When this value approaches 1, the failure rate becomes constant. Similarly,

when value is above 1, the failure rates show increasing trend. This complies with the TTT-plots of the crusher and its components in this study as presented in figure 6. For analysis through TTT-plotting, TBFs of crusher and its components are treated as complete samples. The TTT-

Table 4. Data for TTT-plot of jaw crusher unit.

Serial number of successive failure (n)	Time before successive failure (TBF)	$S_i = (TBF)_i \times \sum(n)$	$U_i = (S_i / S_n)$	$i / \sum n$
1	12	480	0.041	0.025
2	60	2354	0.201	0.05
3	70	2734	0.233	0.075
4	108	4140	0.353	0.1
5	110	4212	0.359	0.125
6	132	4982	0.424	0.15
7	135	5084	0.433	0.175
8	165	6074	0.517	0.2
9	180	6554	0.558	0.225
10	185	6709	0.572	0.25
11	200	7159	0.61	0.275
12	216	7623	0.649	0.3
13	225	7875	0.671	0.325
14	245	8415	0.717	0.35
15	250	8545	0.728	0.375
16	273	9120	0.777	0.4
17	300	9768	0.832	0.425
18	324	10320	0.879	0.45
19	330	10452	0.89	0.475
20	340	10662	0.908	0.5
21	350	10862	0.925	0.525
22	360	11052	0.942	0.55
23	360	11052	0.942	0.575
24	360	11052	0.942	0.6
25	360	11052	0.942	0.625
26	360	11052	0.942	0.65
27	365	11122	0.948	0.675
28	370	11187	0.953	0.7
29	380	11307	0.963	0.725
30	396	11483	0.978	0.75
31	400	11523	0.982	0.775
32	405	11568	0.986	0.8
33	410	11608	0.989	0.825
34	420	11678	0.995	0.85
35	425	11708	0.997	0.875
36	430	11733	1	0.9
37	430	11733	1	0.925
38	431	11736	1	0.95
39	432	11738	1	0.975
40	432	11738	1	1

plots of back toggle, discharge chute liner plate, jaw plate, tie rod and crusher as a unit are presented in figure 6.

3. Result and discussion

The trend and the serial correlation of the data have not contradicted the assumption of iid. The failure rate increases as age and wear take their toll on the crusher and

Table 5. Data for TTT-plot of liner plate.

Serial number of successive failure (n)	Time before successive failure (TBF)	$S_i = (TBF)_i \times \sum(n)$	$U_i = (S_i / S_n)$	$i / \sum n$
1	492	4920	0.78	0.1
2	500	4992	0.792	0.2
3	560	5472	0.868	0.3
4	600	5752	0.912	0.4
5	610	5812	0.922	0.5
6	620	5862	0.93	0.6
7	636	5926	0.94	0.7
8	670	6028	0.956	0.8
9	730	6148	0.975	0.9
10	888	6306	1	1

Table 6. Data for TTT-plot of tie rod.

Serial number of successive failure (n)	Time before successive failure (TBF)	$S_i = (TBF)_i \times \sum(n)$	$U_i = (S_i / S_n)$	$i / \sum n$
1	708	7080	0.812	0.1
2	720	7188	0.825	0.2
3	750	7428	0.852	0.3
4	790	7708	0.885	0.4
5	810	7828	0.898	0.5
6	828	7936	0.911	0.6
7	900	8224	0.944	0.7
8	950	8374	0.961	0.8
9	1100	8494	0.975	0.9
10	1320	8714	1	1

Table 7. Data for TTT-plot of jaw plate.

Serial number of successive failure (n)	Time before successive failure (TBF)	$S_i = (TBF)_i \times \sum(n)$	$U_i = (S_i / S_n)$	$i / \sum n$
1	60	540	0.104	0.111
2	100	860	0.1656	0.222
3	210	1630	0.3139	0.333
4	400	2770	0.5335	0.444
5	556	3550	0.6837	0.556
6	708	4158	0.8008	0.667
7	810	4464	0.8598	0.778
8	1100	5044	0.9715	0.889
9	1248	5192	1	1

Table 8. Data for TTT-plot of back toggle.

Serial number of successive failure (n)	Time before successive failure (TBF)	$S_i = (TBF)_i \times \sum(n)$	$U_i = (S_i / S_n)$	$i / \sum n$
1	396	4356	0.523	0.091
2	455	4946	0.593	0.182
3	567	5954	0.714	0.273
4	600	6218	0.746	0.364
5	650	6568	0.788	0.455
6	711	6934	0.832	0.545
7	767	7214	0.865	0.636
8	790	7306	0.876	0.727
9	800	7336	0.88	0.818
10	800	7336	0.88	0.909
11	1800	8336	1	1

the increasing failure rate also indicates that the entering wear-out phase of the equipment/components. This is illustrated in figures 4 and 5. The steps followed in TTT-plot [15] are outlined in tables 4, 5, 6, 7 and 8. The TTT-Plot for jaw crusher unit concaves downward which reveals increased rate of failures. This is also supported by the shape parameter value 1.17 of Weibull distributions. It also indicates that the jaw crusher as a whole unit is entering the wear-out phase.

The TBFs for liner plate, tie rod and back toggle show an increasing failure rate distribution as its TTT-plot indicates concave downward. This indicates preventive maintenance of the components is to be scheduled before a major failure. The increasing failure rate observation is in agreement with the ML estimation result shown in tables 5, 6 and 8 where the shape parameter for the liner plate, tie rod and back toggle are more than 1, indicating increasing failure rate figures 6(b), (c) and (e). The normal life period is characterized by a low, relatively constant failure rate with failures that are considered to be random cases of stress exceeding strength phase of the equipment/components. It also specifies that the liner plate, tie rod and back toggle are entering the random failure rate phase.

TBFs of the jaw plate indicate decreasing failure rate distribution as its TTT-plot concaves upward figure 6(d). The decreasing failure rate observation is in agreement with the ML result in table 7 where the shape parameter for the jaw plate is less than 1. A decreasing failure rate describes a phenomenon where the probability of an occurrence in a fixed time interval in the future decreases over a time. A decreasing failure rate can describe a period of infant mortality where earlier failures are eliminated and correspond to the situation. Decreasing failure rate also indicates that the early failure of the equipment/components. It also specifies that the jaw plate is the periods of infant mortality

where earlier failures are eliminated and correspond to the situation.

4. Conclusion

The study was aimed to estimate operational reliability of the crusher unit and its critical components using statistical tool like TBF, TTT-plot, LDA, iid, ML estimation, etc. The results of the analysis using a particular tool found in compliance with others.

Nomenclature

β	shape parameter
η	scale parameter
t	running time of equipment/components
i	number of failure
n	number of observations for time between failures
U_i	ratio of S_i/S_n
S_i	is the TTT at time, t_i
S_n	is the TTT at n th failure

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