Study of Reliability Modeling and Performance Analysis of Haul Trucks in Quarries

DASCAR SECARA MONIA CAMELIA, NAN MARIN SILVIU, DASCAR EMIL
The Machine, Installation and Transport Department
University of Petroşani
Str. Universităţii, no.52, 332006, Petroşani
ROMANIA
moniasecara@yahoo.com, nanm@upet.ro, emil.dascar@alcatel-lucent.com http://www.upet.ro/

Abstract: - Trucks are used as hauling machines for transport in open pit, marble quarries. To survive the intense economic competition and complicated environment conditions it is essential that haul trucks are reliable and maintained efficiently. Normal distribution has been used to describe the failures of the individual machine components of a complex system, but different variables and machine particularities, wear or other constrains, determine a real life data following a dynamic large distribution. In this paper, we present the study of the two-parameter Weibull distribution theory and its parameters (shape β and scale α) using Weibull Probability Plotting. Using the failure data for haul trucks in operation at a marble quarry, we obtain the fatigue life equation by regression under different failure probabilities. Weibull distribution analysis for reliability and maintainability is showing a tendency of increasing failure rate, leaving room for decisions on reliability centered maintenance planning, machine improvements, optimal load and the need for review of data collection process.

Key-Words: - Reliability, Weibull distribution, Availability, Maintenance, Monitoring

1 Introduction

Reliability is the probability that parts, components, products and systems will perform the functions for which they were designed without damage under specified conditions, for a certain period of time and with a given confidence level. Although reliability is an independent notion, reliability and the concept of quality are closely related. The quality of a product represents all properties that make it suitable for the intended use; reliability is the ability to keep product quality throughout the operation. In other words, product quality reliability is extended in time [21].

Reliability engineering techniques provide theoretical and practical methods that the likelihood and ability of the parts, components, equipment, products and systems to perform the functions for which they were designed and built, during predetermined time, under specified and known levels confidence, can be specified in advance, designed, tested, proven even under conditions in which they were stored, packaged, transported and then installed, commissioned, monitored and information submitted by all involved and interested.

The reliability of machinery is essential, particularly in quarries, since the breakdown of any machine would cause an unpredictable loss or damage [13]. Therefore, it is obvious that the reliability of such equipment would have considerable impact, not only on production, but also machine life and potentially on human life.

Prevention is better than cure. Instead of allowing the occurrence of failure and suffering from loss or damage of assets and environment, it is always worthwhile forestalling the occurrence. To operate in quarries with reduced number of failures, because of the harsh environment, the machines must be maintained to exhibit high reliability. The maintenance planning of equipment hence requires the orientation of reliability at every stage of its life.

The present study is on effort in this direction that can provide some guidelines while planning the maintenance activities with an orientation to reliability. The most difficult part of this process is the acquisition of trustworthy data. It is known that no amount of precision in the statistical treatment of the data will enable sound judgments to be made based on invalid data.

2 Problem Formulation

Reliability is characterized by four concepts: probability, performance achieved, operating conditions and duration. Operational reliability is

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determined in real operating conditions. In some cases non-economic laboratory experiments, the main source of data collection, are not feasible. Experience in the field is recommending the selection of a group of beneficiaries, by category of use, operating conditions, etc. and systematic tracking performance of products through group reliability. This information is collected through direct reports of the interventions to address the nonconformities. Information processing is done by one of the methods available. Operational reliability is divided in two parts: functional and technological. Functional reliability is known as the operational safety concern matters relating to the operation of the system in terms of primary kinematics [2]. Technological reliability concerns with keeping within the limits of working parameters values. E.g. for a hydro pneumatic cylinder-piston engine, functional reliability is achieved during movements for which the engine was developed and designed; technological reliability means keeping the speed of travel, breaking times, force to the working body.

2.1 Reliability indices

The basic reliability indices, as parameters which express reliability from a quantitative point of view, are being expressed by: the good operating probability, reliability function, $R(t)$; probability of deterioration, non-operation reliability function, $F(t)$; probable density of deteriorations, $f(t)$; intensity or rate of deterioration, $z(t)$; mean time of good operation, *MTBF*; mean time for repairing operations, *MTR*; rate of repairing operations, μ.

Limit failure rate is the ratio of the probability that a device be damaged within the given time estimated $(t, t+dt)$ and the size of the sub-interval dt, since it tends to zero, provided that it is part of the devices that were in good condition early in the process.

Any product lasts and during its use, it is subjected to a process of attrition, a process that usually includes three periods (Fig.1), where upon it, someone must intervene effectively to restore performance to prolonged use, namely:

- Initial period, when the number of faults that occur when running are relatively high, but decreasing;

- Normal period (useful) life, when defects are reduced in number and random;

- The final period, when the number of failures due to wear or aging phenomena is growing.

Looking from probabilistic perspective at the reliability problem [4], it can be said that time when a malfunction occurs cannot be establish with certainty, but only as a probability linked to a confidence interval.

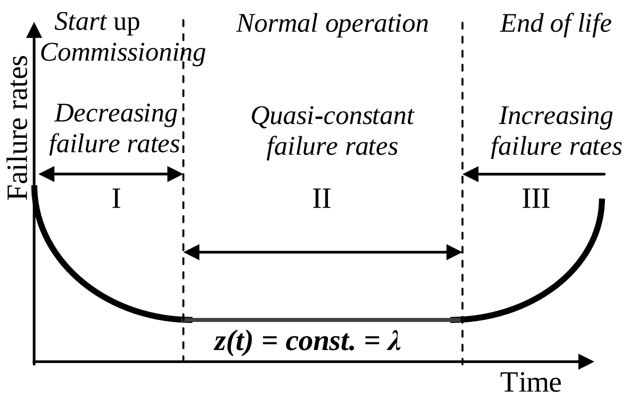

Fig.1 The evolution of failures on the entire life of a product

The concept of reliability has the statistical character in addition to the probabilistic. This is explained by the fact that the determination of reliability is based on data obtained by measurements (laboratory), or through operational monitoring of the product, when obtain data on defects found on samples. As Reliability function [22] is recognized as survival function:

$$R(t) = P(T \geq t),, \qquad (1)$$

and has the following properties:

$R(t)$ is a continuous function of time, for each

$$t > 0,\ 0 \leq R(t) \leq 1, \qquad (2)$$

where: T - random variable of running time up to the failure; t - time limit of the good working period.

$$R(t) = 1 \text{ for } t = 0, \qquad (3)$$

at the initial moment, when system starts to operate, it sureley works.

$$\text{Lim } R(t) = 0, \qquad (4)$$

after a period of time, sufficient likelihood of better functioning decreases after a certain law, until it reaches zero.

$$\text{For } t_1 < t_2 \text{ results } R(t_1) > R(t_2), \qquad (5)$$

so it’s a decreasing function. The probability that a system will not fail in the time interval $[a, b]$ is:

$$P(a<T<b) = R(a) - R(b) \qquad (6)$$

2.2 Graphic Systems

Matrix of defects shows the number of failures recorded on each component of the system at equal time intervals. The number of failures shall sum horizontally, for each component during the experiment. The corresponding histogram is built as a matrix, which is Pareto chart of the system. Pareto chart is in the form of a histogram showing the number of defects registered to a time "t" of each of the components of a system.

Pareto chart allows highlighting the component with the lowest reliability in a system. Complex Pareto charts rises in successive steps to highlight simple elements with the highest rate of falls. The goal is to find Pareto analysis of subsystems that affect overall system failure, characterizing the frequency of subsystems failures and ranking system for each subsystem failure. Pareto Chart is a priority failure analysis showing overall subsystem.
Then fault numbers are added together vertically, to the intervals. At the bottom of the matrix it builds a histogram showing the evolution of the number of failure time intervals Δt of the entire system. Since the probability density function is a good time:

$$f(t) = \frac{n(\Delta t)}{N_0 \cdot \Delta t} \quad (7)$$

N_0 and Δt are constant, the histogram is representing the histogram of *f(t)* but at a different scale.

2.3 Weibull Distribution

Sometimes there are physical arguments based on the probabilistic failure mode which tends to justify the choice of model. The models are used only because of its empirical success in real data failure sheet. We choose the calculation of reliability by Weibull model.

Weibull model is a very flexible method for modeling data sets containing values greater than zero, such as failure data. Weibull analysis can make predictions about the life of a product, compare the reliability of competing products, can establish policies to guarantee statistical or proactively manage stocks of spare parts [3]. Weibull analysis is primarily a graphical technique although it can be done analytically.

One graphical technique is Weibull Probability Plotting [15]; other graphical methods are Maximum Likelihood Estimation or Hazard Plotting.

Weibull distribution is characterized by three parameters:

- α (alpha), shape parameter; shows the stretching on the time axis of the Weibull distribution law.
- β (beta), scale parameter or characteristic life; changes the shape of variations of reliability curves.
- γ (gamma), location parameter or min. life.

The Weibull distribution density function [5], [10], [17] is given by the probability PDF:

$$f(t,\beta,\alpha,\gamma) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \quad (8)$$

With: $\beta > 0, \alpha > 0, t \geq 0, \gamma \geq 0$

The cumulative Weibull distribution function [15], [20], [9] is given by the cumulative distribution, CDF:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \quad (9)$$

Where: β (beta) is the shape parameter, α (alpha) is the scale parameter, γ (gamma) is the location parameter.
Formulas and properties [12]:

Reliability: $$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (10)$$

Failure rate: $$h(t) = \frac{\beta}{t}\left(\frac{t}{\alpha}\right)^{\beta-1} \quad (11)$$

Properties:

- Mean Rank: $\alpha \cdot \Gamma\left(1 + \frac{1}{\beta}\right)$ (12)
- Median Rank: $\alpha \cdot (\ln 2)^{\frac{1}{\beta}}$ (13)
- Variation:

$$\alpha^2 \cdot \Gamma\left(1 + \frac{2}{\beta}\right) - \left[\alpha \cdot \Gamma\left(1 + \frac{1}{\beta}\right)\right]^2 \quad (14)$$

Where: Γ (gamma), gamma function with value of Γ(*N*) for the entire *N*.

$$\Gamma(N) = (N-1)! \quad (15)$$

From equation (10) we determine time before failure, TBF:

$$t = \alpha \cdot (-\ln R(t))^{\frac{1}{\beta}} \quad (16)$$

To determine the relation between the CDF and the two parameters (β, α), we take the double logarithmic transformation of the CDF.
Considering γ=0, we have:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (17)$$

$$1 - F(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (18)$$

$$\ln\left(\frac{1}{1-F(t)}\right) = -\left(\frac{t}{\alpha}\right)^{\beta} \quad (19)$$

$$\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right] = \beta \ln t - \beta \ln \alpha \quad (20)$$

Equation (20) is an equation of a straightline. To plot *F(t)* versus *t*, we follow three steps:

a) Rank estimates in an ascending order

To estimate $F(t_n)$, one method of calculation formula is applied (Table 1). Where: N=TotalRank, is total number of data points; n=Rank, is the rank number of the given nonconformity.

Methods for estimating $F(t_n)$

Method	**$F(t_n)$**	
Mean Rank	$\frac{n}{N+1}$	(21)
Median Rank	$\frac{n-0.3}{n+0.4}$	(22)
Symmetrical CDF	$\frac{n-0.5}{N}$	(23)

In our calculation, having a sample size less than 100, will consider the Median Rank method (Bernard's approximation), formula (22).

b) Estimate $F(t_n)$ of the n^{th} failure

c) Plot $F(t_n)$ versus t

Cumulative Weibull distribution function *F(t)* can be rearranged in a form to which we apply the linear regression. The rearranged *F(t)*:

$$y(t) = \ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right] = -shape \cdot \ln(scale) + shape \cdot \ln(t) \quad (24)$$

$$y = intercept + slope \cdot t \quad (25)$$

y(t) is a linear function of ln*(t)* having *slope*=β and *intercept*=–$\beta\ln\alpha$, the basis for the linearization of the Weibull CDF (Fig.2). It has been shown [1], [23] that shape factor drops directly out of the regression equation, whilst the scale factor has to be derived from the intercept:

$$scale = exp\left(-\frac{intercept}{shape}\right) \quad (26)$$

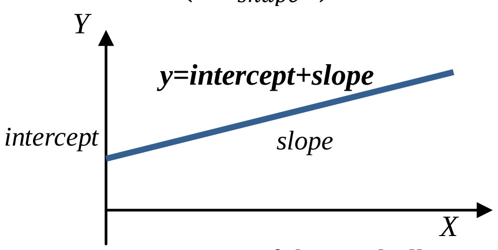

Fig.2 Linearization of the Weibull CDF

2.4 Mean Time Before Failure (MTBF)

After a system is repaired, it does not have the same performance characteristics as a new one, because not always the repair of defective components is perfect, the system has suffered overheating components, or broken parts were not well repaired. The best estimate of the total MTBF for Weibull distribution [14], [15] is given by:

$$MTBF = \alpha \cdot \Gamma\left(1+\frac{1}{\beta}\right)+\gamma \quad (27)$$

MTBF parameter value estimated using this statistical method often cannot be calculated because of incomplete field data.

In most cases, this time decreases randomly with age, which demonstrates that there is a series of random factors that make the average cycle time to decrease. If all system faults can be rectified, implying a long service life of the system, the estimated average cycle time becomes constant, obviously taking into account the age of the system. This is known as steady state condition. Uptime and disruption may change depending on system's age:

$$MTBF = \frac{T}{N} \quad (28)$$

Where: T is total working time of the system; N is total number of faults.

MTBF parameter value estimated using this methodology must be corrected in order to reach a value as close to reality as possible, requiring a certain level of confidence. Correction factors can be achieved using the confidence interval method.

3 The Work Metodology

In this subsection, we provide a data set assumed to be distributed with Weibull law (see [12], pp. 83, 100). The data sets (Table 1) were recorded in a time period of 1 year for a number of 8 haul trucks in use at an open pit, marble quarry [8]:

Table 1

#	TTR	CTTR	Cause	TBF	CTBF
1	14	14	Engine	430	430
2	31	45	Gear box	770	1200
3	9	54	Transmission	1690	2890
4	8	62	Others-exhaust	488	3378
5	32	94	Engine	800	4178
6	13	107	Brakes	1784	5962
7	12	119	Suspension	456	6418
8	16	135	Gear box	886	7304
9	7	142	Transmission	1328	8632
10	9	151	Transmission	1460	10092
11	11	162	Brakes	16	10108
12	8	170	Steering	920	11028
13	4	174	Others-frame	218	11246
14	8	182	Transmission	77	11323
15	11	193	Brakes	680	12003
16	41	234	Engine	1650	13653
17	26	260	Gear box	501	14154
18	13	273	Brakes	1150	15304
19	14	287	Brakes	1000	16304
20	10	297	Suspension	88	16392
21	7	304	Steering	156	16548
22	7	311	Transmission	800	17348
23	14	325	Brakes	420	17768
24	12	337	Suspension	60	17828
25	10	347	Suspension	340	18168
26	8	355	Others-frame	196	18364

3.1 Pareto Analysis

The frequency of failures of each component or subsystem can be determined using the Pareto principle, or 80-20 rule [1], which states that for many events, 80 % of the effect was caused by 20% of the cause (Fig.3):

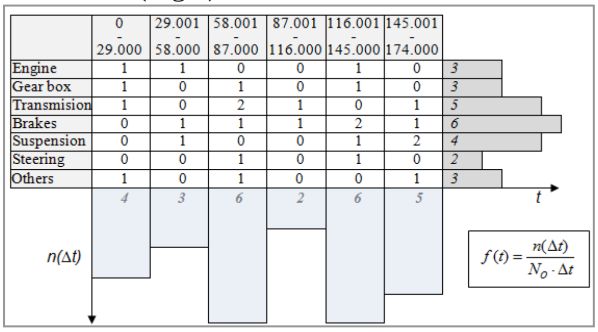

Fig.3 Frequency of failures

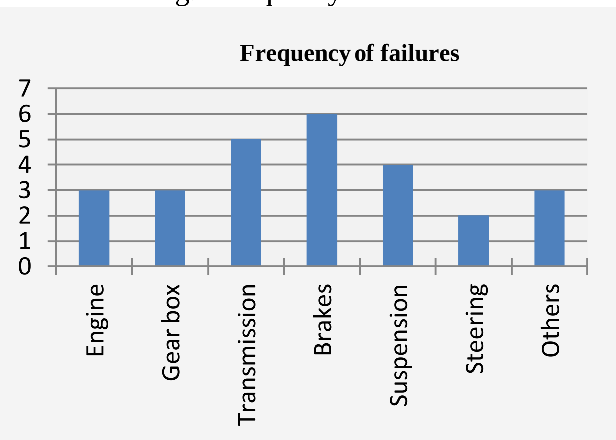

Fig.4 Pareto chart on the absolute incidence of faults

Trend analysis (Fig.4) of the system does not show any trend, the method proves that the system deteriorates [14]. System reliability is an indicator of the condition of the equipment's overall performance; reliability analysis was done using each subsystem failure. Pareto chart is then analyzed to select the most important components affecting the system.

3.2 Application methods for calculating reliability - Weibull

Calculating only the MTBF to represent the system reliability could lead to misleading and unnecessary spares expenses, or not enough spares to continue work effectively. Failures are not normally distributed; MTBF does not provide information about the changing nature of failure rates over time. The high value of the mean time to repair subassemblies, namely the mean intensity or repair rate, is explained by the difficulty of corrective maintenance work, given the large masses and working gauges.

To provide reasonable accurate failure analysis and failure forecasts with a limited number of samples, we have chosen Weibull method because it provides a performance analysis using a simple and useful graphical plot of the failure data.

3.2.1 Preparing to analyze

Weibull analysis requires some preparatory calculations: MedianRank column is an estimate of the proportion of the population that fails until the time listed in column TBF (Time Before Failure).

To generate the graph of the corresponding regression, Weibull Analysis needs to generate median ranks as median values on the Y axis values, ranks obtained with the method of calculating Median Ranks, formula (22), where n=1,2, ... 26; N=26 (total number of failures), Table 2.

The advantage of this method is that data corresponding to *ln(ln(1/(1-MedianRank)))* is graphical awarded in a straight line. By performing a simple linear regression we obtained estimated parameters which allow inferences on TBF values. To do this, in next step we used Excel add-in Analysis ToolPak to calculate the parameters (Table 2) required to estimate Weibull parameters:

Table 2

TBF	n	1/(1-n)	ln(ln(1/(1-n)))	ln(TBF)
430	0.0265	1.0272	-3.6166	6.0637
1,200	0.0643	1.0688	-2.7096	7.0900
2,890	0.1022	1.1139	-2.2266	7.9690
3,378	0.1401	1.1629	-1.8904	8.1250
4,178	0.1780	1.2165	-1.6293	8.3375
5,962	0.2159	1.2753	-1.4137	8.6931
6,418	0.2537	1.3401	-1.2284	8.7668
7,304	0.2916	1.4117	-1.0646	8.8961
8,632	0.3295	1.4915	-0.9167	9.0632
10,092	0.3674	1.5808	-0.7809	9.2194
10,108	0.4053	1.6815	-0.6544	9.2210
11,028	0.4431	1.7959	-0.5352	9.3081
11,246	0.4810	1.9270	-0.4216	9.3277
11,323	0.5189	2.0787	-0.3122	9.3345
12,003	0.5568	2.2564	-0.2060	9.3929
13,653	0.5946	2.4672	-0.1018	9.5217
14,154	0.6325	2.7216	0.0012	9.5577
15,304	0.6704	3.0344	0.1043	9.6358
16,304	0.7083	3.4285	0.2087	9.6991
16,392	0.7462	3.9402	0.3157	9.7045
16,548	0.7840	4.6315	0.4271	9.7140
17,348	0.8219	5.6170	0.5456	9.7612
17,768	0.8598	7.1351	0.6755	9.7851
17,828	0.8977	9.7777	0.8242	9.7885
18,168	0.9356	15.529	1.0089	9.8074
18,364	0.9734	37.714	1.2892	9.8181

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3.2.2 Estimation of Weibull parameters

Weibull cumulative distribution function can be transformed so that it appears as a straight line.

Using Excel Data Analysis [24], with ToolPack Analysis kit, we generated a new set of data represented in Table 3.

Table 3

#	Predicted =ln(ln(1/(1-n)))	Residuals
1	-3.4009	0.6912
2	-2.1514	-0.0752
3	-1.9296	0.0391
4	-1.6274	-0.0019
5	-1.1219	-0.2917
6	-1.0171	-0.2112
7	-0.8333	-0.2313
8	-0.5958	-0.3209
9	-0.3737	-0.4072
10	-0.3714	-0.2830
11	-0.2476	-0.2876
12	-0.2197	-0.2018
13	-0.2100	-0.1022
14	-0.1271	-0.0788
15	0.0559	-0.1578
16	0.1071	-0.1059
17	0.2182	-0.1138
18	0.3081	-0.0994
19	0.3158	-0.0001
20	0.3293	0.0978
21	0.3964	0.1492
22	0.4304	0.2450
23	0.4352	0.3890
24	0.4620	0.5468
25	0.4773	0.8119
26	0.4773	0.8119

3.2.3 Fitting a line to the data

With data calculated in Table 3, next step was to generate the graphical representation for the two entries which determine the reliability curve:

- Predicted ln(ln(1/(1-n)))
- Residuals

Data plotted on X-axes, *ln(TBF)*, and Y-axes, ln(ln(1/(1-n))), has been further adjusted to create the linear distribution:

- Linear ln(ln(1/(1-n)))

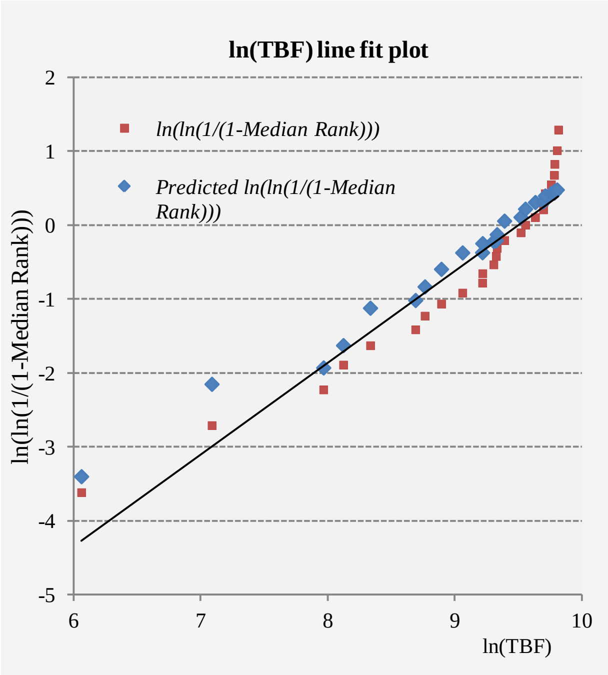

Fig.5 Predicted line

Survival probability and reliability were determined by selecting 20 intervals of 1,000 hours *(X)* together with Microsoft Office Excel formula:

$$\text{WEIBULL}(X,\alpha,\beta,TRUE) \quad (29)$$

The results were entered into Table 4.

Table 4

TBF	Reliability		TBF	Reliability
0	1.0000		21,000	0.1422
1,000	0.9746		22,000	0.1245
2,000	0.9334		23,000	0.1087
3,000	0.8846		24,000	0.0946
4,000	0.8314		25,000	0.0822
5,000	0.7760		26,000	0.0712
6,000	0.7199		27,000	0.0616
7,000	0.6642		28,000	0.0531
8,000	0.6098		29,000	0.0457
9,000	0.5572		30,000	0.0392
10,000	0.5070		31,000	0.0336
11,000	0.4594		32,000	0.0287
12,000	0.4147		33,000	0.0245
13,000	0.3729		34,000	0.0209
14,000	0.3342		35,000	0.0177
15,000	0.2985		36,000	0.0150
16,000	0.2658		37,000	0.0127
17,000	0.2359		38,000	0.0108
18,000	0.2088		39,000	0.0091
19,000	0.1842		40,000	0.0076
20,000	0.1621		-	-

3.2.4 TBF for a certain reliability level

Sometimes we need time before failure for a certain reliability level, given through the requirements. We performed the calculations using formula (16).

Table 5

Reliability	TBF
0.01	38,432
0.10	23,601
0.50	10,143
0.90	2,696
0.99	516

3.2.5 Generate the survival chart

Using data from Table 4, the reliability chart is:

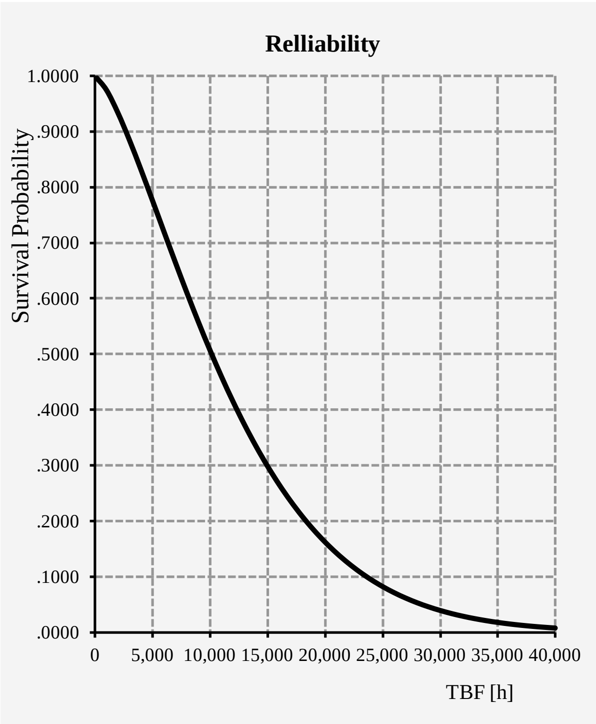

Fig.6 Survival graph, *β=1.42*

4 Conclusion

This study is restrained to a relative small number of equipments investigated (8 haul trucks). The accuracy of the data collected is depending on the people concerned with maintenance activities, the collection in a systematic and organized way of failure/repair reports (understanding that this could be time consuming and requires proper processes in place). The equipment performance depends on its age and other factors. It is critical to record failure/repair data in such manner that can be used by the management team for spare parts provision, maintenance planning, ordering new equipment, or taking corrective actions about factors that have an influence on the equipment reliability (load, speed, roads, etc).

Performance of a quarry not only depends upon production equipment like drills/cutters/excavators/ loaders but very much affected by the availability and utilization of service equipment. An integrated study of availability of all the equipment in a quarry can definitely improve the productivity through enhanced utilization of production equipment based on their availability.

Weibull shape parameter β indicates if the failure rate is increasing, constant or decreasing [10]. In our study we found $\beta > 1.0$ indicating an increase in the rate of failures. This is typical to products presenting the phenomenon of wear. In this study Weibull model shows that for a confidence level of 99 %, TBF has a value of at least 2,696 hours. To increase the reliability it is absolutely necessary to address, using also the analysis performed with Pareto charts, the major nonconformities on each subsystem: brakes, transmission, suspension, engine, gearbox, running system. Along with that, it is necessary to review the data collection process.

Repairs of major systems may take several days and often requires removing other components to carry out the work. Effective identification, planning, scheduling and execution can significantly reduce the impact of these failures. Eliminating failures primarily through a valid predictive maintenance would have the greatest positive impact.

Another main cause of failure is a combination of truck speed, payload and road conditions. If any of these three cases is eliminated, the problem is minimized. A review of load conditions and truck speed are needed, also an evaluation of the road conditions which are a major cause of equipment downtime because of damages to the brakes and suspension. The cycle of freeze / thaw that perhaps last several months, determine a significant wear of roads, the holes appeared having the potential to cause significant damage to major mechanical components. Combining the data monitored by the pressure dampers, payload and GPS coordinates, it is possible to successfully locate inadequate road sections. This would allow an intelligent operation of road maintenance teams with a priority list of road sections requiring repair operations.

While mining equipment wears, availability tends to decrease. The biggest challenge for a truck to operate within 90% availability is the sustainability of a robust maintenance program. Quality maintenance team is represented by the high availability of equipment which may be achieved through the development of consistent processes for maintaining equipment to world-class standards. An integrated part of the maintenance program is to remove old components, worn or that have reached the end of their useful life, and replace them with components that meet the standards of durability and reliability.

Another key element of success is monitoring program describing the collection of routines that facilitate early detection of changes in the functionality of the equipment and systems. These processes support a method of repair before the failure of equipment. In its simplest form, condition monitoring involves studying the state machinery, systems and components, as well as external factors.

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