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Failure Rate Analysis of Shovel and Dumper in Opencast Limestone Mine using RWB and ANN

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Abstract: ***To develop a nonparametric bathtub curve model for a shovel and dumper in an opencast limestone mine, the historical failure data such as time between failure (TBF) and failure frequency of a shovel and dumper were collected from the mine. Based on the collected TBF and failure frequency, Weibull parameters i.e., shape parameter (β), scale parameter (η) and location parameter (γ) were calculated under the K-S test (Kolmogorov–Smirnov). A Weibull distribution model has been developed to obtain the probability distribution function (PDF) and the bathtub-shaped failure rate curve for a shovel-dumper system using Reliability Isograph Workbench (RWB). Also, the Artificial Neural Network (ANN) model has been developed to predict the PDF and failure rate for the same shovel-dumper system and compared with the obtained values of Reliability Isograph Workbench. It was found that the values of RMSE and R^2 were 5.96E-5 & 0.999 for PDF and 9.23E-8 & 0.9993 for failure rate respectively.***

Index Terms: ***Nonparametric model, Bathtub curve, lifetime estimation, Failure rate, Opencast limestone mine, K-S test, Weibull distribution, Time between failure, Failure frequency, RMSE (Root mean square error) and ANN.***

I. INTRODUCTION

The ageing of the equipment used in opencast mines has become a significant issue for utilization, because of the increase in failure rate [1]. Therefore, the reliability of equipment may be affected, when the system is more susceptible to failure. In a shovel-dumper system, the common subsystems such as breaking subsystem, differential subsystem, drive train, hydraulic cylinders, undercarriage, electrical subsystem, hydraulic subsystem, engine subsystem, are responsible for 80 to 90% of the regulatory asset-based utilization. These components will play a very important role in reliability analysis for the long run.

The statistical approach to obtain the failure rate of the shovel-dumper system can be classified into two groups, the parametric and nonparametric statistical models [1]. However few methodologies have been found in literature even for

mining equipment such as shovel and dumper. The K-S test has been used to find the Weibull parameters through a nonparametric statistical method based on the collected data i.e. the TBF, TTR and to account for the uncertainty in failure and repair rate [2]. In addition, the estimation of failures is very close to the estimation of the shovel and dumper useful life which may be analyzed through bathtub curve plotted between TBF (t) along the abscissa and failure rate ($\lambda(t)$) along the ordinate [3].

In the bathtub curve, the failure rate or probability of failure within the total lifetime of equipment is clearly represented by three stages of failure and the built for shovel-dumper in opencast limestone mine using the Weibull distribution with α, β and γ [4] – [6].

In Figure 1 [7], the first stage represents by decreasing the failure rate (β<1). The second stage is a useful life (β=1) where low and constant failure rate. In the third stage, the wear out (β>1), there is an increasing failure rate due to the ageing of the shovel and dumpers [7].

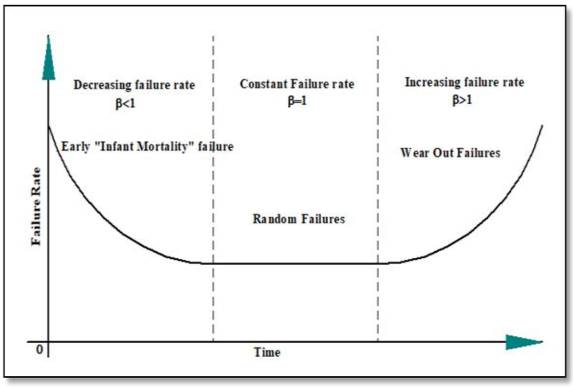

Fig. 1. Bathtub curve (a schematic)

II. Case Study and Data Collection

The study was carried out at The Thummalapenta Limestone Mine (Ultra Tech Cement Ltd mine) which is placed at Ramnagar, Tadipatri, Andhra Pradesh State. In the present study, data related to TBF and failure frequency were collected for two years, considering the match factor 1:4 (one shovel & four dumpers) one shovel namely S1 having capacity 6.5 cubic meter and four dumpers i.e., D1, D2, D3 and D4 having capacity 60 Tones each were considered.

III. Estimation of MTBF

The basic failure data is analyzed using the trend test and series correlation test [8]. It can provide statistical

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measurements of mean time between failure (MTBF) for the shovel and dumpers considered. However, the maximum likelihood estimation (MLE) is the method that tests the originally collected failure data of a shovel and dumpers. The calculated MTBF from failure data (TBF and failure frequency) by the equations (1) given below [9].

$$MTBF = \frac{\sum_{n=1}^{n}(t_1 + t_2 + t_3 ... t_n)}{n} = \frac{\text{Total Operating Time}}{\text{Total No. of Failures}} \quad (1)$$

Where, MTBF-Mean time between failure, t-Time interval, n-Number of Failures

The summary of the failure data of one shovel S1 and four dumpers D1, D2, D3 & D4 from the field such as MTBF and failure frequency are shown in Table 1.

Table. 1 Summary of failure characteristics for S1, D1, D2, D3 & D4 in a limestone mine

Systems	No. of Failures	Failure Frequency in %	MTBF in hr
S1	92	21.8	108.39
D1	91	21.56	129.04
D2	87	20.62	131.15
D3	76	18.01	176.51
D4	76	18.01	162.41
Total	422	100	

S-Shovel, D*-Dumper*

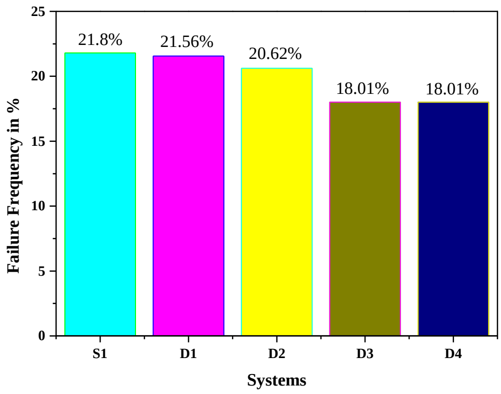

Fig. 6. Failure frequency of shovel and dumpers

After classification and segregating failure frequency, failure codes and failure data (TBF and TTR) related to a shovel and each dumper were arranged as per the requirements of Isograph Reliability Workbench. As per the interpretation, the shovel and each dumpers having different failure frequency such as S1 having 21.08%, D1 having 21.56%, D2 having 20.62%, D3 having 18.01% and D4 having 18.01% as shown in Figure 1.

IV. Kolmogorov–Smirnov test (K-S) test

The K-S test is used to analyze the best-fit distribution functions for TBF data of the shovel S1 and dumpers D1, D2, D3 & D4. The values of β, η and γ are obtained directly by fitting the data collected (TBF & TTR) from the mine to cumulative failure functions (cumulative TBF & TTR) or the cumulative reliability functions conducted using the RWB software package. The estimated Weibull parameters of the best-fitted distribution function of a shovel and dumpers for TBF are listed in Table 2.

Table. 2 Best fit the distribution of S1, D1, D2, D3 & D4 for TBF

Sl. No	System	Best Fit	Weibull Parameters		
			η	β	γ
1	S1	Weibull 2P	390	4.8	-190
2	D1	Weibull 3P	1.1E2	1.7	0
3	D2	Weibull 3P	97	1.3	3.2
4	D3	Weibull 1P	1.6E3	3.5	-57
5	D4	Weibull 1P	90	2.2	0

P-Parameters*

V. Estimation of the probability density function

The PDF was obtained by using Maximum Likelihood Estimation using equation (2) [10] under Isograph Reliability Workbench are given Table 3. The probability of a shovel and dumpers can never be greater than 1 applies to the value of the MTBF at any point. This means that the integral of the MTBF over any interval must be less than one. If the PDF at MTBF is greater than 1, remember that there is no area under a point, meaning there is no probability under a point.

$$f(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\eta^{\beta}} e^{-(\frac{t-\gamma}{\eta})^{\beta}} = \lambda(t) \times R(t) \quad (2)$$

Where, f (t)-PDF, λ(t)-Failure Rate, R(t)-Reliability Function

Table. 3 The probability density function of S1, D1, D2, D3 & D4

Sl. No	Systems	Weibull Parameters			MTBF in hr	PDF
		η	β	γ		
1	S1	390	4.8	-190	108.39	0.00347
2	D1	1.1E2	1.7	0	129.04	0.00541
3	D2	97	1.3	3.2	131.15	0.00533
4	D3	1.6E3	3.5	-57	176.51	0.00641
5	D4	90	2.2	0	162.41	0.00768

From Figure 2, it is observed that the PDF of the shovel (S1) is 0.00347 at MTBF= 108.39 hours with β = 4.8 (β>1) for the dumpers D1, D2, D3, D4 are 0.00541, 0.00533, 0.00641 & 0.00768 with different MTBF (129.04, 131.15,176.51&162.41hours)and(1.7, 1.3, 3.5 & 2.2) respectively. The PDF of a shovel and each dumper is less than unity, therefore it can be concluded that the PDF of a shovel and each dumper were found to reject the null hypothesis at 5% (0.05) level of consequence for obtained data [10] [11]. Also, collected failure data of a shovel and dumpers are 95% (0.95) of the probability of success rate.

The PDF for the given distribution of a shovel and each dumper in the probability that has continued i.e. the graph of this density function will be continuous over its range less than unity. This is because it is defined over a continuous variable and also a continuous range of values.

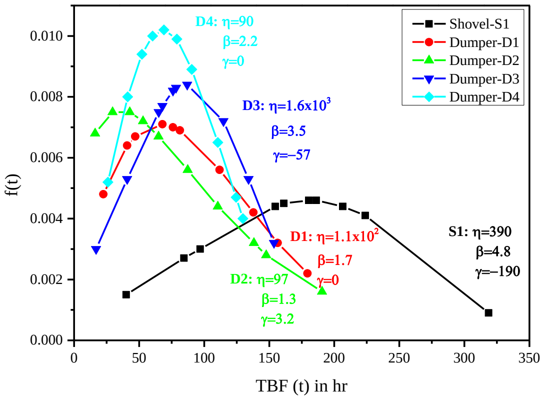

Fig. 2. Probability density function for S1, D1, D2, D3 & D4 with different Weibull parameters

VI. Simulation of Failure Rate

The summary of the obtained failure rate λ(t) for given MTBF of a shovel and dumpers as mentioned in Table 4. Also, the numerical interpretations were carried out using equation (3) for failure rate [10].

$$\lambda(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\eta^{\beta}} \tag{3}$$

Table. 4 Failure rate and behaviour of the bathtub curve for S1, D1, D2, D3 & D4.

Sl. No	Systems	Weibull Parameters			MTBF	λ(t)	Failure behaviour
		η	β	γ			
1	S1	390	4.8	-190	108.39	0.0107 8	(β>1)
2	D1	1.1E2	1.7	0	129.04	0.0132	(β>1)
3	D2	97	1.3	3.2	131.15	0.0122 1	(β>1)
4	D3	1.6E3	3.5	-57	176.51	0.0181 3	(β>1)
5	D4	90	2.2	0	162.41	0.0211 5	(β>1)

Figure 3, 4 and 5 are the plots between TBF on the X-axis and failure rate on Y-axis, the plots were made for the data of two working years of a shovel and each dumper respectively. It can be experiential that the increasing failure rate of the plotted bathtub curve resembles the same as shown in Figure 1 but this bathtub curve model posses only the increasing failure regions.

In Figure 3, the nature of the graph represents the failure time of an increasing failure rate for the shovel (S1) having β ranged from 4.8. It is observed that there is a rapid increase in failure rates i.e., entering the "wear out" phase and a fixed pattern of failures can be expected of the shovel (S1) for the period of two years (effective working hours: 7200 working hours) [2], [11].

Similarly, in Figure 4, 5, 6, and 7, the nature of the graph represents the increasing failure rate for dumpers such as D1, D2, D3 and D4 for the period of 2 years with different values of β, which is greater than one. There is a rapid increase in failure rates i.e., entering the "wear out" phase and a fixed pattern of failures can be expected [2], [12].

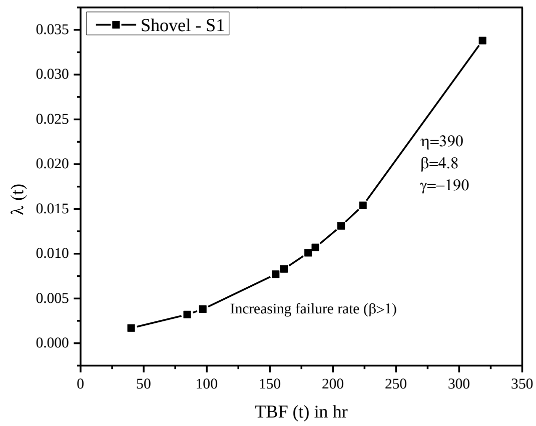

Fig. 3. The failure rate of shovel-S1

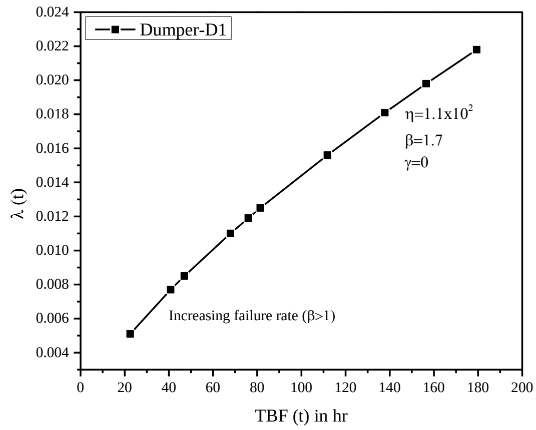

Fig. 4. The failure rate of Dumper D1

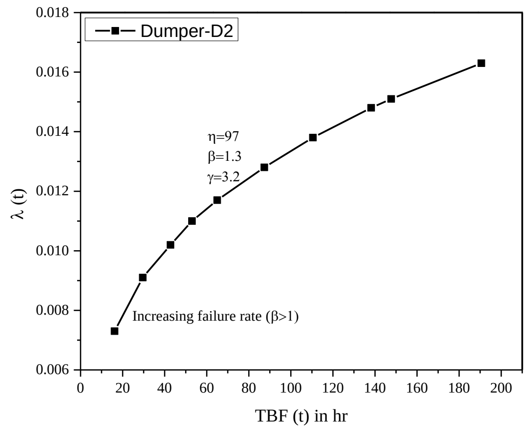

Fig. 5. The failure rate of Dumper D2

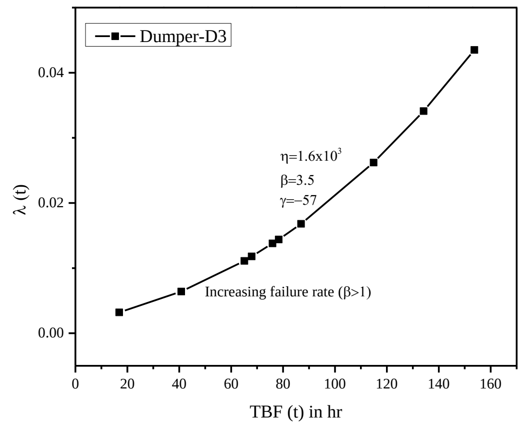

Fig. 6. The failure rate of dumper D3

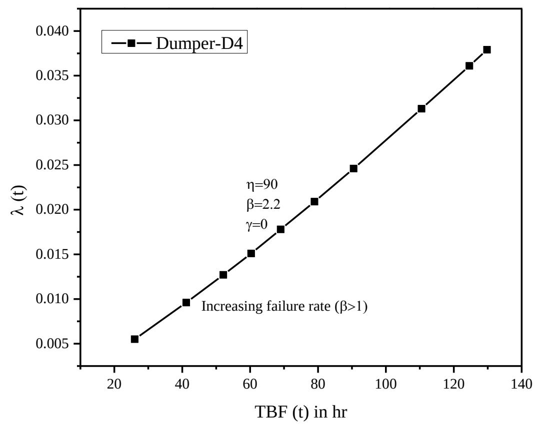

Fig. 7. The failure rate of dumper D4

Due to a rapid increase in the failure rate of S1, D1, D2, D3 and D4, The reliability of all equipment are very less. In this case, Improvement of reliability is required based on preventive maintenance. The preventive maintenance schedule of this equipment may increase up to 80% or reliability [2], [12].

VII. Development and simulation of ANN model for PDF and Failure rate

In this current work, the failure data of S1, D1, D2, D3 and D4 were collected from mine and calculated PDF and failure rate. ANN model expected to predict PDF and rate of failure of a shovel and each dumper in the opencast limestone mine is shown in Figure 6. The neural structure was modelled with 3 parameters as input, output and hidden layer in the middle of the input layer. Four parameters were taken from MTBF, β and η and γ, two parameters are PDF and failure rate in the output layer.

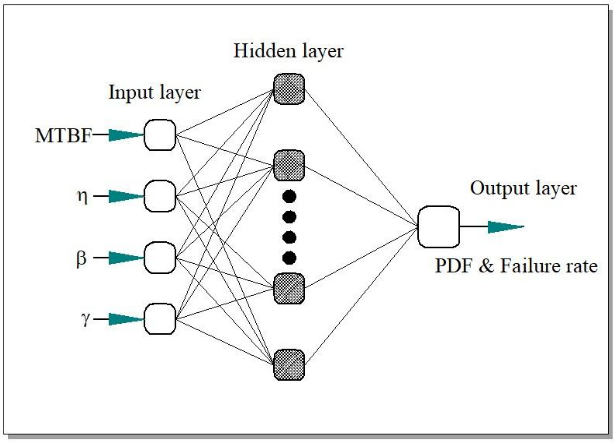

Fig. 8. ANN model

In this model, 5 sets of input and output data were taken i.e., only 3 sets of data were used for training, one set of data for testing and the rest of a single set of data for validation. The propagation learning algorithm was applied back to the learning of the current form. These input and output sample data are required to be normalized for the predictive before modelling the neural structure. The following equation (4) was used to normalize the data among -1 to 1 [13].

$$Y = (High_{Value} - Low_{Value})\frac{Y_i - Y_{Min}}{Y_{Max} - Y_{Min}} + Low_{Value} \qquad (4)$$

Where Y-Obtained Value

In this study, LM learning algorithm was used in the training process. Neural networks from the direct feed forward to two layers (ie, a hidden layer) can adapt to any relationship between input and output if there are enough neurons in the hidden layer. The layers that are not removed are called hidden layers as shown in Figure 6. The number of neurons in the hidden layer is estimated using the trial and error technique [13]. In a hidden layer of 5 and 8 neurons of the PDF rate and failure rate respectively. In general, more difficult problems require more neurons, possibly more layers. The simplest problems require fewer neurons. Each neuron model has been trained more than 30 times. This training algorithm adjusts weights and biases frequently to reduce the error between the values obtained from the RWB and the expected values of the ANN model. It has been found that LM with 5 neurons forPDF and 8 neurons for better failure rate due to lower error and higher R^2 value. The training performance of different neural models is presented in Tables 5 and 6.The performance of different models was based on RMSE and R^2, which are considered using equation (5) and (6) correspondingly [13]. In Table 5 and 6, it has been observed that the RMSE and R2 values are 5.96E-5 and 0.999 for PDF and 9.23E-8 and 0.9993 for the failure rate in LM-5 and LM-8 respectively.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y - y')^2} \qquad (5)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y - y')^2}{\sum_{i=1}^{N}(y')^2} \quad (6)$$

y – Obtained Value, y'-Predicted Value, N-Number of Samples

Table. 5 The training performance of PDF for different neurons

No. of Neurons	R^2	RMSE
5	**0.9999**	**5.96E-5**
6	0.9818	3.94E-4
7	0.9409	6.35E-4
8	0.9913	5.86E-3

Table. 6 The training performance failure rate for different neurons

No. of Neurons	R^2	RMSE
5	0.9999	4.45E-5
6	0.9999	9E-5
7	0.9817	1.01E-3
8	**0.9993**	**9.23E-8**
9	0.9994	8.42E-5
10	0.9993	9.06E-5

Table 7 shows a comparison of the values obtained by RWB with the predicted values of the optimal ANN model with LM-5 and LM-8 and their error in Table 7. In Table 7, the maximum error was 9.04E-05 in the sample -5 and smallest error is -9.33E-05 in sample-1 in PDF and the maximum errors is 0.000151 in sample-2 and the smallest error is -4.27E-08 in the sample -1 in failure rate.

Table. 7 Comparison of the obtained and predicted values

Sl. No	Systems	Weibull Parameters			MTBF in hr	Obtained values by RWB		Predicted Values by ANN		Error	
		η	β	γ		PDF f(t)	λ(τ)	PDF f(t)	λ(τ)	PDF f(t)	λ(τ)
1	S1	390	4.8	-190	108.39	0.00347	0.01078	0.003563	0.01095	-9.33E-5	-0.000177
2	D1	1.1×102	1.7	0	129.04	0.00541	0.0132	0.005398	0.01304	1.19E-5	0.000151
3	D2	97	1.3	3.2	131.15	0.00533	0.01221	0.005352	0.01248	-2.21E-5	-0.000278
4	D3	1.6×103	3.5	-57	176.51	0.00641	0.01813	0.006418	0.01813	8.91E-6	-4.27E-8
5	D4	90	2.2	0	162.41	0.00768	0.02115	0.007589	0.02114	9.04E-5	9.24E-8

Regression, one of the most normally used statistical methods, estimates the associations between obtained and predicted values by RWB and ANN, respectively. Regression models give an entirely adaptable system for depicting and testing theories about the association between obtained and predicted values. The regression chart for LM-5 and LM-8 is shown in the training, testing and validation process in Figure 9 and 10. In Figure 9 and 10 R^2 is the closest to the unit, and gives the mathematical model is given by equation (7) and (8) for PDF and failure rate of a shovel and dumpers respectively [13], [14].

$$y = (2.3186 \times E - 4) + (0.95988\ )\ x \quad (7)$$

$$y = (0.3048 \times E - 4) + (0.98338\ )\ x \quad (8)$$

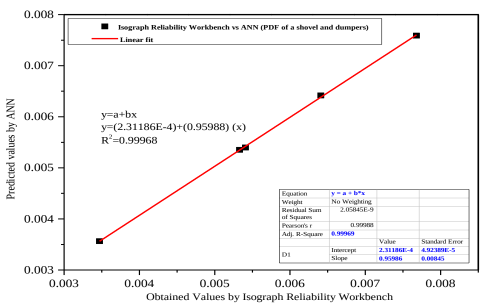

Fig. 9. PDF: Regression plot for obtained and predicted values

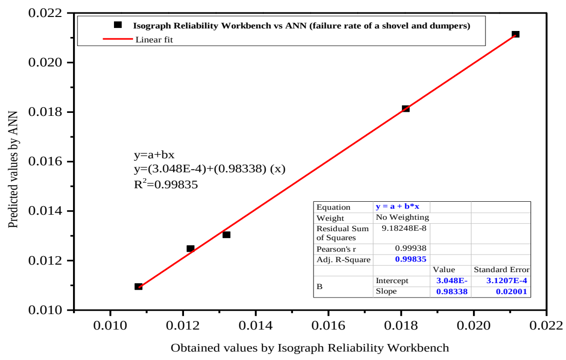

Fig. 10. Failure Rate: Regression plot for obtained and predicted values

VIII. Conclusion

In this paper, a bathtub curve model is plotted for the estimation of the probability density function, failure rate along with lifetime distribution of shovel S1 and dumpers D1, D2, D3 D4 used in opencast limestone mine for the period of 2 years (effective working hours: 7200 hours). The influencing Weibull parameters β, η, & γ were found from the observation and result obtained. It is concluded that there is a rapid increase in failure rates i.e., entering the "wear out" phase and a fixed pattern of failures can be expected of the shovel-dumpers system and also suggested that, planned preventive maintenance schedule for the remaining working hours to an extent good reliability.

The ANN model was constructed with four input coefficients, MTBF, β, η & γ and two output parameters such as PDF and failure rate. The Levenberg - Marquard algorithm is used with feedforward propagation to derive the optimal current model. LM learning algorithms were found with 5 neurons for PDF and 8 neurons for failure rates of in the hidden layer were optimally based on statistical error analysis. The values obtained and predicted values of PDF and failure rate of a shovel and dumpers with the highest R^2 value give satisfactory results with a statistical mathematical model.

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Nomenclature

TBF	Time between failures
TTR	Time to repair
MTBF	Mean time between failures
RMSE	Root mean square error
MLE	Maximum likelihood estimation
K-S test	Kolmogorov–Smirnov test
FB Propogation	Forward back propagation
R(t)	Reliability function
Y	Obtained values
X_A	Actual value
X_P	Predicated value
$\overline{X}$	Average value
Y	Obtained value
R^2	Coefficient of determinations
b_j	Bias
W_{ij}	Weights

Greek Letters

β	Shape parameter
η	Scale parameter
γ	Location parameter

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