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ASSESSING STATISTICAL METHODS AND RELIABILITY MODELS FOR RELIABILITY FUNCTION ESTIMATION IN THERMAL POWER PLANTS

PROCENA STATISTIČKIH METODA I MODELA POUZDANOSTI ZA ODREĐIVANJE FUNKCIJE POUZDANOSTI U TERMOELEKTRANAMA

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Keywords
- thermal power system
- reliability
- mathematical distributions
- statistical methods

Abstract

The assessment of fossil-fuel power plant reliability is of critical importance not only for operation and maintenance, but also for long-term planning and development of energy systems. The thermal power system examined in this study comprises three subsystems, with the reliability evaluation carried out using a thirteen-year failure database covering the normal service life. The reliability analysis employs several mathematical reliability models, including two-parameter Weibull, normal, lognormal, and simple exponential distributions. Parameters of each distribution are estimated using three independent statistical techniques: the graphical method (based on probability papers), method of moments (MoM), and maximum likelihood estimation (MLE) method. While the two-parameter Weibull distribution estimated by interval-censored MLE represents the most appropriate unified model for reliability analysis in terms of interpretability and decision relevance, regression analyses in this study demonstrates that the Normal distribution estimated by MoM achieves the best overall fit to the experimental data. The obtained results confirm that the application of rigorous probabilistic methods and models can provide a reliable foundation for maintenance optimisation, enhanced safety and strategic management of thermal power systems.

Ključne reči
- termoenergetski sistem
- pouzdanost
- matematičke raspodele
- statističke metode

Izvod

Procena pouzdanosti termoelektrana je od presudnog značaja ne samo za eksploataciju i održavanje, već i za dugoročno planiranje i razvoj energetskih sistema. Termoenergetski sistem razmatran u ovom istraživanju se sastoji se od tri podsistema, pri čemu je ocena pouzdanosti sprovedena na osnovu trinaestogodišnje baze podataka o otkazima tokom normalnog radnog veka. Analiza pouzdanosti izvedena je primenom više matematičkih modela pouzdanosti, među kojima su dvoparametarska Vejbulova raspodela, normalna, lognormalna i prosta eksponencijalna raspodela. Parametri svake raspodele određeni su korišćenjem tri nezavisne statističke tehnike: grafičke metode (zasnovane na papirima verovatnoće), metode momenata (MoM) i metode maksimalne verodostojnosti (MLE). Iako dvoparametarska Vejbulova raspodela, procenjena intervalno-cenzurisanim MLE postupkom, predstavlja najadekvatniji jedinstveni model za analizu pouzdanosti u pogledu tumačenja i relevantnosti za odlučivanje, regresiona analiza u ovom istraživanju pokazala je da normalna raspodela procenjena metodom momenata pruža najbolje ukupno slaganje sa eksperimentalnim podacima. Dobijeni rezultati potvrđuju da primena rigoroznih metoda verovatnoće i modela može obezbediti pouzdanu osnovu za optimizaciju održavanja, povećanje sigurnosti i strateško upravljanje termoenergetskim sistemima.

INTRODUCTION

The reliability of thermal power plants constitutes a key factor in the energy security and efficiency of power systems, given that such plants still account for a significant share of the global energy mix, particularly in countries with a heavy reliance on fossil fuels /1, 2/. High equipment reliability ensures stability of electricity supply, optimisation of maintenance costs and reduction of risks associated with unplanned outages. Research emphasizes that the reliability of thermal power facilities is strongly linked to material degradation processes, wear of rotating and stationary components, as well as cumulative effects of thermomechanical cycles /3/. The essential problem related to the maintenance of complex systems and structures is related to the challenges of predicting the failure behaviour of the components with due account of associated uncertainties.

Reliability analyses have been significantly advanced through the application of modern statistical methodologies, including partially censored data, robust estimators and hierarchical Bayesian models /4-6/. Particular attention has been devoted to the two-parameter Weibull distribution, which due to its flexibility enables the modelling of different failure regimes (infant mortality, random failures and wear-out phase) within the same mathematical framework /7/. Alongside the Weibull distribution, normal and lognormal models are frequently employed, especially when failure processes arise from cumulative or multiplicative random effects /8/, while the exponential distribution is typically applied in specific cases where a constant failure rate is assumed.

Contemporary literature highlights the necessity of adapting statistical models to real operating conditions, which includes accounting for an increasing failure rate due to wear-out phenomena, handling partially observed data (censoring) and limited sample sizes, as well as incorporating information from SCADA/EMS systems and predictive maintenance algorithms /9/. In this context, the paper presents an integrated procedure for parameter estimation using the graphical method, the method of moments (MoM) and maximum likelihood estimation (MLE). Their performance is compared on empirical failure data from a thermal power plant using the root mean square (RMS) deviation as the principal accuracy criterion.

DATA COLLECTION AND CLASSIFICATION

An exploitation study on the reliability of the thermal power system in power plant ‘Nikola Tesla, Block A4’ (TENT-A4, installed capacity 308.5 MW) was conducted for the period 1996-2008. The failure evidence required to determine the reliability and unreliability indicators of the system is presented in Table 1. For the purpose of system analysis, the operating time intervals are defined on a yearly basis, corresponding to 8760 operating hours.

In this study the thermal power system is represented as a set of three subsystems: fossil fuel boiler, steam turbines, and three-phase alternator. System boundaries are adopted in order to determine the transmission limits of the thermal power subsystems within the thermal scheme. The control limit that encloses the thermal power system does not encompass: systems for storage and delivery of fuel, systems for collecting and treatment of cooling water, the block transformer and the ash dump.

Quantitative analysis of equipment failures by reliability engineering methods is generally founded on the assumption that systems can be represented in two discrete states: functioning or faulty. While the overall performance of many systems (e.g., power generation, manufacturing, or production systems) may operate at various levels of nominal capacity depending on the condition of their components, the reliability of thermal power systems can still be assessed through binary quantification techniques /10, 11/.

Within reliability analysis, failures of repairable systems are commonly assumed to be independent and random. The inherently stochastic nature of the properties and behaviour of technical systems constitutes one of the defining features of the reliability concept. Accordingly, a fundamental component of reliability analysis for complex systems is the proper characterisation, representation, propagation and interpretation of uncertainty /12/.

Table 1. Exploitation reliability components of the thermal power system at TENT-A4.

Observation period				Time					Reliability						
i	Tk_i	$T_{i\text{-}1}$ T_i	Ta_i	Tpz_i	Tnz_i	$Trez_i$	Tr_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	Nt_i	f_i	F_i	R_i	λ_i	MR
	[year]	[h]	[h]	[h]	[h]	[h]	[h]	[-]	[-]	[-]	[h^{-1}]	[-]	[-]	[h^{-1}]	[-]
1	2	3 4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1996	0-8760	5456	2199.25	617.24	487.11	5943.11	15	15	176	0.08	0.08	0.92	0.0852	7.70
2	1997	8760-17520	6962	1078.38	529.38	189.44	7151.44	13	28	163	0.07	0.15	0.85	0.0800	14.47
3	1998	17520-26280	6756	1062.25	590.54	350.41	7106.41	14	42	149	0.07	0.22	0.78	0.0940	21.80
4	1999	26280-35040	5894	2126.36	372.38	366.46	6260.46	9	51	140	0.05	0.27	0.73	0.0643	26.50
5	2000	35040-43800	6584	1345.1	477.25	353.25	6937.25	15	66	125	0.08	0.35	0.65	0.1200	34.32
6	2001	43800-52560	6533	733.54	1212.57	280.09	6813.09	26	92	99	0.14	0.49	0.51	0.2626	47.9
7	2002	52560-61320	7176	746.01	597.56	240.03	7416.03	17	109	82	0.09	0.58	0.42	0.2073	56.8
8	2003	61320-70080	7234	862.17	405.09	258.34	7492.34	14	123	68	0.07	0.65	0.35	0.2059	64.11
9	2004	70080-78840	7035	1169.57	547.12	7.51	7042.51	14	137	54	0.07	0.72	0.28	0.2593	71.42
10	2005	78840-87600	7172	908.45	424.35	254.40	7426.40	15	152	39	0.08	0.80	0.20	0.3846	79.26
11	2006	87600-96360	7113	508.39	993.49	144.32	7257.32	17	169	22	0.09	0.89	0.11	0.7727	88.14
12	2007	96360-105120	1878	6430.39	239.27	211.54	2089.54	6	175	16	0.03	0.92	0.08	0.375	91.27
13	2008	105120-113880	8443	0	272.57	44.03	8487.03	16	191	0	0.08	1.00	0	$+\infty$	99.63

METHODOLOGY

The key question is which theoretical distribution best represents the data. While physical features of the stochastic process may hint at its form, the mathematical form of the distribution is often difficult to infer solely from empirical data /13/.

In this study, four probabilistic models are employed: the two-parameter Weibull, normal, lognormal and exponential distributions. Their performance is assessed with respect to three functions: reliability $R(t)$, failure density $f(t)$, and failure rate $\lambda(t)$. The root mean square (RMS) deviation between model predictions and empirical observations is employed as the principal accuracy criterion, facilitating a quantitative comparison of the estimation methods and distributional models.

The analysis is conducted on the basis of interval-grouped failure time data from the thermal power plant system which represents a realistic scenario in which failures are recorded in time blocks /14/. Under such conditions, standard estimation methods require adaptation, particularly with respect to handling partially censored samples /15/.

Various methods can be employed to quantify system reliability. A fundamental challenge in reliability analysis arises from the uncertainty inherent in failure occurrences and their consequences. The parameters of each distribution are estimated by three independent statistical techniques: graphical method (based on probability plots), method of moments (MoM), and maximum likelihood estimation (MLE) method.

The graphical method involves data transformation and linearisation on probability papers (Weibull, normal, log-normal and exponential). This approach is conceptually straightforward and enables visual validation of model fit /16-20/, yet in practice it has been shown to be less accurate compared to numerical procedures. After calculating the failure probabilities, the corresponding cumulative percentages of failures (t_i, $F(t_i)_{50\%}$) are plotted on probabilistic papers. Median ranks (Benard's approximation) are used instead of other ranking methods since they are at a specific confidence level (50%). Use of graphical method and probability papers to identify a class of distribution functions and estimate their parameters, except their relative simplicity, offers several advantages that extend beyond the scope of routine engineering practice. Moreover, the graphical method can often provide deeper insights into the behaviour of repairable systems.

The method of moments (MoM), where interval mid-points are repeated according to the number of failures, yield representative estimates of the mean and variance of the distribution. This method is frequently applied in energy-related studies due to its simple implementation /7/, but it may produce larger deviations when data are limited or when the distribution exhibits strong skewness.

The maximum likelihood estimation (MLE) method is widely recognised in literature as the most reliable approach for censored data /6, 7/, particularly in the case of the Weibull distribution, where it can yield consistent and unbiased estimates even with small samples. This study also employs interval-censored maximum likelihood estimation, a variant of MLE that maximizes the log-likelihood function.

Through this integrated approach, reliable conclusions can be drawn regarding the applicability of individual models under real-world operating conditions of a thermal power plant.

RESULTS AND DISCUSSION

A graphical comparison between the empirical reliability and the two-parameter Weibull distribution curves, obtained using different methods, is presented in Fig. 1. Due to considerations of space and brevity, analogous presentations for the remaining three distributions have been omitted.

The estimated parameters together with the root-mean-square (RMS) deviations for all analysed distributions (Weibull, normal, lognormal and exponential) and models (graphical, MoM, MLE and interval-censored MLE) are summarised in Table 2. A lower RMS deviation reflects a higher degree of statistical conformity and indicates superior model adequacy in representing the empirical reliability data.

The three-parameter Weibull distribution is tested as well, but the estimates consistently drove the threshold parameter γ toward zero, with no significant improvement in RMSD, effectively reducing the model to the two-parameter Weibull distribution. Uncensored 3p Weibull distribution is weakly identified by MLE, driving β to the search boundary and degrading fit. This could be a symptom of limited temporal resolution and insufficient early-life information.

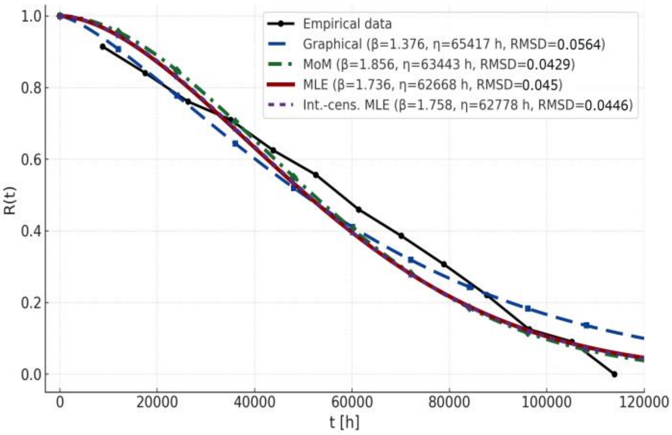

Figure 1. Empirical reliability and two-parameter Weibull distribution curves.

Table 2. Comparative evaluation of statistical distributions and estimation methods for reliability function $R(t)$.

Distribution	Method	Parameters	RMSD
Weibull (2p)	Graphical	$\beta = 1.376$, $\eta = 65417$	0.0564
Weibull (2p)	MoM	$\beta = 1.856$, $\eta = 63443$	0.0429
Weibull (2p)	MLE	$\beta = 1.736$, $\eta = 62668$	0.045
Weibull (2p)	Inter.-cens.MLE	$\beta = 1.758$, $\eta = 62778$	0.0446
Normal	Graphical	$\mu = 57239.8$, $\sigma = 32578.6$	0.03815
Normal	MoM	$\mu = 57239.8$, $\sigma = 32740.9$	0.03742
Normal	MLE	$\mu = 57239.8$, $\sigma = 32740.9$	0.03742
Normal	Inter.-cens.MLE	$\mu = 56906.5$, $\sigma = 32492.2$	0.03852
Lognormal	Graphical	$\mu\_ln = 10.808842$, $\sigma\_ln = 0.707586$	0.06949
Lognormal	MoM	$\mu\_ln = 10.808842$, $\sigma\_ln = 0.747299$	0.06942
Lognormal	MLE	$\mu\_ln = 10.808842$, $\sigma\_ln = 0.747299$	0.06942
Lognormal	Inter.-cens.MLE	$\mu\_ln = 10.691342$, $\sigma\_ln = 0.843678$	0.0876
Exponential	Graphical	$\theta = 38603.45$, $\lambda = 2.59E-5$	0.20826
Exponential	MoM	$\theta = 61320$, $\lambda = 1.63E-5$	0.10112
Exponential	MLE	$\theta = 61320$, $\lambda = 1.63E-5$	0.10112
Exponential	Inter.-cens.MLE	$\theta = 56827.66$, $\lambda = 1.76E-5$	0.11294

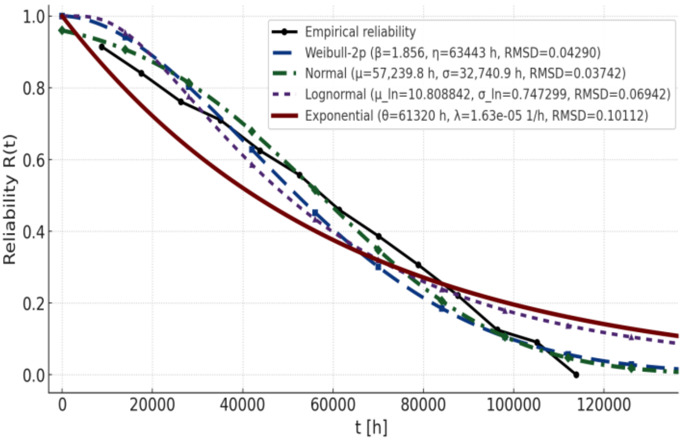

Figure 2. Comparison of empirical reliability with best-fit curves across all distributions and methods.

Figure 2 presents a comparison of empirical reliability with the theoretical curves yielding the minimum RMS deviation for each distribution and estimation method, thereby highlighting the upper performance bounds of the applied models and methods.

The reliability analysis demonstrates that normal and two-parameter Weibull distributions provide the most accurate representations of empirical data, with RMSD values as low as 0.037-0.039 for the normal model and 0.043-0.056 for the Weibull-2p, depending on the estimation method. Lognormal and exponential models show substantially poorer agreement, confirming that a constant failure rate assumption is not appropriate for the studied system.

The normal distribution yields the lowest RMSD, an outcome likely attributable to the coarse annual data grouping. Despite the small numerical differences, the normal distribution is theoretically less suitable for reliability applications, as it may assign nonzero probabilities to negative failure times (a physically implausible outcome). Therefore, its use in this context is limited to approximate analyses. From both mechanistic and operational standpoints, Weibull-2p is regarded as the most meaningful model for interpreting reliability, owing to its flexibility and its established role as the standard in reliability analyses.

Estimates of β from the Weibull-2p model are consistently in the range of 1.7-1.8, with the exception of the graphical method, thereby indicating an increasing failure rate consistent with aging and wear-out mechanisms.

In terms of scientific interpretability and decision relevance, Weibull-2p with interval-censored MLE represents the most appropriate unified model for reliability analysis, providing the most defensible methodological framework by properly accounting for censoring and minimising placement bias. Nevertheless, in this case the MoM yields the lowest RMS deviation for both the Weibull-2p and normal distributions, demonstrating that MoM can serve as a practical compromise when a simple and rapid assessment is required. While practical for rapid estimation, the graphical method exhibits the greatest variability and consistently produces higher RMS deviations than MoM or MLE. It remains valuable for preliminary parameter estimation.

Figures 3 and 4 present comparisons of the empirical failure density and failure rate, in respect, with theoretical curves of the two-parameter Weibull, normal, lognormal and exponential distributions. For each distribution, the most accurate parameter estimates obtained by the corresponding estimation method are displayed, and the legend reports the RMS values that quantify deviations from the experimental data.

The empirical failure density shows a clear mid-life peak followed by decline. RMSD comparisons indicate that the normal distribution estimated by MoM provides the smallest deviation from the empirical curve ($\approx 3.6 \cdot 10^{-6}$ h^{-1}), with the Weibull-2p distribution estimated by MoM close behind. Lognormal and exponential fits perform worse, reflecting structural mismatches with the observed timing of failures. These differences, although numerically small in per-hour units, correspond to meaningful deviations when expressed on annual scales.

The normal distribution achieved the lowest RMSD by placing probability mass in a broad central window ($\approx 40 \cdot 10^3$ - $80 \cdot 10^3$ h), consistent with the bulk of empirical observations. However, it underestimates early failures and fails to capture irregularities in the late tail. The Weibull-2p model ($\beta \approx 1.86$, $\eta \approx 63.4 \cdot 10^3$ h) also produces a close fit, with slightly higher RMSD, but offers greater interpretability. Its unimodal, right-skewed form aligns with physical expectations of wear-out processes, making it more suitable for reliability inference. By contrast, the lognormal distribution overemphasizes early failures and produces an excessively heavy tail, resulting in the largest RMSD. The exponential distribution, constrained to a monotonically decreasing density, is structurally mis-specified, underfitting the mid-life peak, although its RMSD is only moderately worse than Weibull's due to coarse annual averaging.

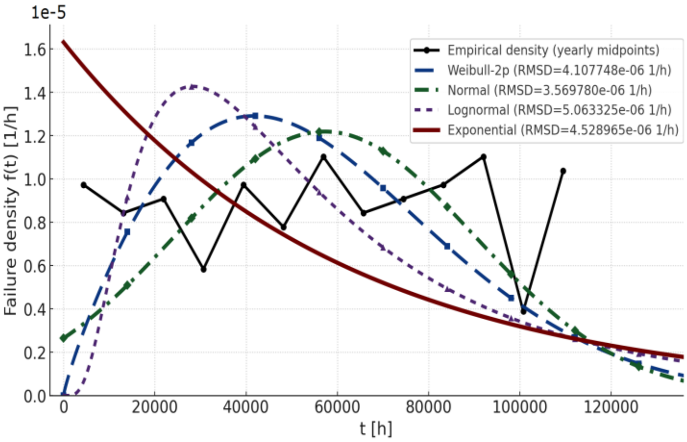

Figure 3. Comparison of empirical failure density with best-fit curves across all distributions and methods.

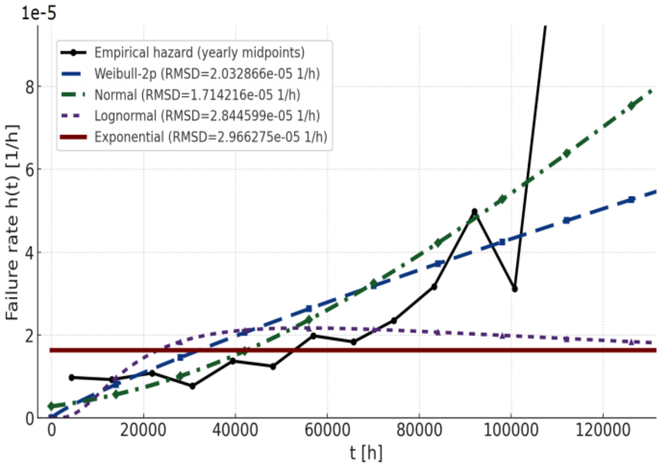

Figure 4. Comparison of empirical failure rate with best-fit curves across all distributions and methods.

Although the normal distribution provides the tightest descriptive fit of the failure density at the annual scale, the Weibull-2p model achieves nearly comparable accuracy while offering superior scientific interpretability, making it the preferred framework for reliability engineering analysis and policy.

The empirical failure rate function reconstructed from annual counts shows a clear upward trend, with noticeable volatility in later years due to the small survivor pool. RMSD comparisons indicate that the normal distribution estimated by MoM provides the smallest deviation ($\approx 1.7 \cdot 10^{-5}$ h^{-1}), closely followed by the Weibull-2p estimated by MoM

($\approx 2.0 \cdot 10^{-5}$ h^{-1}), while the lognormal and exponential models perform substantially worse. The normal model captures the smoothed annual trend most closely, but its failure rate lacks interpretability, whereas the Weibull-2p aligns with wearout processes and provides a physically meaningful framework for reliability analysis. It tracks the empirical rise well but slightly underestimates the steepest increments and overestimates at early times, yielding a marginally larger RMSD than the normal distribution. By contrast, the lognormal failure rate, which peaks and then declines, conflicts with the monotone late-life increase observed in the data, while the exponential distribution, constrained to a constant failure rate, systematically misfits both early and late stages.

These findings emphasise the influence of temporal aggregation, which favours gradually varying failure rate and penalizes non-monotone or constant forms. For planning and policy, Weibull-2p remains the most defensible choice, combining near-optimal fit with strong interpretability, while the normal distribution may serve as a descriptive benchmark for communicating trends.

CONCLUSIONS

This study evaluates the two-parameter Weibull, normal, lognormal and exponential distribution models on 13 years of operational data from a thermal power system in a thermal power plant. Four estimation methods - graphical (median-rank), method of moments (MoM), uncensored maximum likelihood estimation (MLE) and interval-censored MLE - are applied and the adequacy of each distribution is assessed against empirical reliability, failure density and failure rate reconstructed from annual records.

Across the reliability function, the normal and Weibull-2p consistently deliver the closest descriptive fits, while the exponential distribution performs the worst. Normal with MoM or MLE produces the lowest RMSD, closely followed by Weibull-2p with MoM. Lognormal is consistently weaker at late times, and the Weibull-3p offers no identifiable benefit with threshold estimates collapsing toward zero.

For failure density, the normal model places mass centrally and achieves the smallest RMSD, while the Weibull-2p is nearly as accurate but more consistent with an accelerating aging process. Lognormal peaks prematurely and decays too slowly and the exponential again fails to represent the mid-life concentration of failures.

Analysis of the failure rate function confirms a monotone increase with age, consistent with wear-out. Here, the Weibull-2p with $\beta > 1$ provides the most mechanistically interpretable model, while normal tracks the aggregated trend but lacks a physically grounded form. Lognormal and exponential failure rates, by contrast, conflict with the observed late-life risk increase.

Methodologically, the method of moments (MoM) yields the lowest RMS deviation for both the normal and Weibull-2p distributions, while uncensored MLE produces competitive results. The graphical method exhibits the greatest variability and consistently generates higher RMS deviations than MoM or MLE, though it remains practical for rapid estimation.

From the standpoint of scientific interpretability and decision relevance, the Weibull-2p distribution estimated by interval-censored MLE emerges as the most appropriate unified model for reliability analysis, offering a defensible methodological framework that properly accounts for censoring and minimises placement bias. At the same time, the MoM produces the lowest RMS deviation for both Weibull-2p and normal distributions, underscoring its value as a practical compromise in contexts where rapid and straightforward assessment is required.

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Nomenclature

MR - medial rang (=(j-0.3)/(n+0.4)), [-]
n - total number of failures in the reported period, [-]
Nn - total number of failures, [-]
$\sum_{i=1}^{n} Nn_i$ - cumulative sum of failures, $\left(j = \sum_{i=1}^{n} Nn_i \right)$, [-]
Nt - reverse cumulative sum of failures, [-]
Ta - engaged time, [h]
Tk - calendar time, [year]
Tnz - total time of unplanned outages, [h]
Tpz - total time of planned outages, [h]
Tr - mean time available (= $Ta + Trez$), [h]
$Trez$ - total standby time (= $Tk - (Ta + Tpz + Tnz)$), [h]

Greek letter symbols

β - shape parameter, [-]
γ - threshold parameter, [h]
η - scale parameter, [-]
θ - scale parameter (mean life), [h]
λ - failure rate, [1/h]
μ - mean (location parameter), [-]
σ - standard deviation (scale parameter), [-]

Subscript

i - number of operating interval

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