Multi-Variate Weibull Model for Predicting System-Reliability, from Testing Results of the Components

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SUMMARY AND CONCLUSION

This paper discusses the problem of system reliability prediction by accelerated testing results on its components. This problem appears when the testing of a system as a whole either has high cost or may be impossible in a short period of time, especially at the beginning of development.

A multi-variate Weibull model is proposed to utilize testing results of components in predicting system reliability with reduced test length and minimized cost. Prediction of system reliability in a given situation means that we must know how to calculate not only the point estimation of reliability index, but also the Lower Confidence Bound (LCB) with given confidence probability q (q = 0.8-0.95). In this case our goal is to give the algorithm for calculating not by approximation for LCB (based as a rule on Normal distribution of point reliability estimation), but exact LCB corresponding to a given confidence probability.

1. INTRODUCTION

In the paper it is assumed, that the system consists of N components for which failures are statistically independent and for each of them the Weibull life-time distribution is used with scale parameter β_i and shape parameter α_i, i=1, . . . N. For each component the test results are obtained using sensors to provide the data.

On the basis of this data the authors offer the algorithm for calculating the LCB with a given confidence level for system reliability prediction.

There are a lot publications in this area, last of them one can find in [4, 12], but no one before apparently discussed the multi-variate Weibull model.

For these components there are not only well developed algorithms for calculating point and interval reliability estimates but corresponding software such as SuperSMITH/99 developed by one of the authors.

The initial information for rapid reliability prediction can be obtained as a result accelerated testing of product. The accuracy of reliability prediction often depends on how accurately the actual degradation (failure) process is simulated for accelerated testing. The results of the product degradation (failure) process include data on the mechanical, chemical, electrical, thermal, radiation, etc. effects. For example, the mechanical types of degradation process are deformation, crack, wear, creep, etc. In real life these different processes act simultaneously, in a connection and interaction on the product. Therefore, accurate accelerated testing includes simultaneous combination of different types of testing (mechanical, environmental, electrical, radiation, etc.) [14], [15], with the assumption that the failures are statistically independent. However, ignoring this fact gives a lower estimation of system reliability. Methods which could take into account the failure dependence would require more additional information.

In this paper only series systems are considered, but the proposed methodology can be extended also to systems with arbitrary series-parallel structures.

1.1 NOTATION

$R(t)$	system reliability function;
t	operation time (hours, cycles, etc.);
T_0	given value of operation time;
$R_i(t)$	component's reliability function;
N	the number of components (i = 1,. . . , N);
β_i	Weibull distribution shape parameter;
α_i	Weibull distribution scale parameter;
u_i	$\ln \alpha_i$;
$\underline{b_i}$	$1/\beta_i$;
$\bar{R}$	point estimate of any parameter R;
δ_i	r_i/n_i
n_i	sample size for component of type i;
r_i	the number of failures for component of type i;
$L(\varepsilon,v)$	(1-ε)-th quantile of the distribution of random variable vB-U;
R_q	LCB for parameter R of level q;
z_q	quantile of level q for normal distribution;
$\underline{q}$	statistical confidence level.
$\bar{R}'$	the value of the statistic $\bar{R}(t)$ from (3.4) after calculation of the estimates parameters u_i and b_i, i = 1, ...N;

1.2 LIST OF ASSUMPTION

1. The system operates until the failure.

2. Each component used in system is s-independent.
3. Each component has the Weibull distribution time to failure with different and unknown shape and scale parameters.
4. There are N independent censored samples for each component as follows:

$$t_{(1)}^{(i)} \le t_{(2)}^{(i)} \le \ldots \le t_{(ri)}^{(i)}, \quad i = 1, \ldots, N, \quad r_i \le n_i$$

2. CONFIDENCE BOUNDS FOR SIMPLE WEIBULL MODEL.

Let us consider first of all the simple Weibull model and algorithm for calculating of LCB for reliability function $R_i(t)$, $i = 1 \ldots N$, of each component separately (index i will be dropped in this section for simplicity).

If we use the Weibull model for the life time τ of the component, we can write the reliability index for this component as

$$R(t) = \exp\{ -(\frac{t}{\alpha})^{\beta} \}, \ t > 0, \qquad (2.1)$$

where: i is a variable generally given in terms of time or cycles;
α is the scale parameter, β is the shape parameter of the Weibull distribution.

The expression (2.1) can be transformed into the following:

$$R(t) = \exp\{ -\exp(\frac{\ln t - u}{b})\}, \ t \,.\, 0, \qquad (2.2)$$

where $u = \ln a$ and $b = 1/\beta$ are the shape and scale parameters of the random variable $x = \ln \tau$, t will be held fixed in the further. Assume n units are tested and let $t_1, t_2, \ldots t_r$ be failure data and $t_{r+1}, t_{r+2}, \ldots t_n$ be censored data (either failure or time censoring).

The methodology of calculating the point and interval estimations of reliability function R(t) applied to simple Weibull model has been developed in many publications [3, 6-10] and can be described as follows.

Denote by $\bar{u}$ and $\bar{b}$ estimates of the parameters $u = \ln\alpha$ and $b = 1/\beta$, for which the distribution of the ratios

$$B = \bar{b}/b \ \text{ and } \ U = (\bar{u} - u)/b$$

is independent of the unknown parameters. Here, the distribution of the random variables is determined only by the estimation method and the test plan (that is, by the numbers n and r).

The indicated estimated types include maximum likelihood estimates, the best linear estimates, and the best linear invariant estimates [6], as well as the linear estimates in [7]. Tables of the coefficients for calculating the estimates $\bar{u}$ and $\bar{b}$ by censored samples are presented in the indicated papers. For the estimates of the types indicated above, one can introduce the function

$L(\varepsilon, \nu)$, $\varepsilon \in R^1$, such that $P\{L(\varepsilon, \nu) < \nu B - U\} = \varepsilon$

that is, $L(\varepsilon, \nu)$ is the $(1 - \varepsilon)$-th quantile of the distribution of the random variable $\nu B - U$.

The function $L(\varepsilon,\nu)$ decreases with increasing value of ε (for fixed ν) and increases with increasing value of ν (for fixed ε). This form is independent of the parameters u and b and is determined only by the form of the estimates $\bar{u}$ and $\bar{b}$ and the test plan (that is, by the numbers n and r).

We denote

$$L^*(\varepsilon, \nu) = \exp\{-\exp[-L(\varepsilon, \nu)]\}, \qquad (2.3)$$

extending its definition by its continuity property to the set

$\{(\varepsilon\ \nu);\ \varepsilon \in [0.1],\ \nu \in R^1\}$, setting $L^*(o, \nu) = 1$ and

$L^*(1,\nu) = 0$ for all $\nu \in R^1$

Tables of values of $L^*(\varepsilon, \nu)$ for different forms of the estimates $\bar{u}$ and $\bar{b}$ are presented in [6-9]. For example, for the linear estimates Johns and Liberman [7] presents tables of the function

$L^*(\varepsilon, \nu)$ for $\varepsilon = 0.5, 0.75, 0.8, 0.9$ and for censoring $\delta = r/n$,

which is close to the values of 0.25, 0.5, 0.75, and 1. For large volume samples, n>30, the normal approximation of the function

$$L(\varepsilon, \nu) \approx \nu - z_\varepsilon \sigma / \sqrt{n}, \qquad (2.4)$$

where σ depends only on ν and δ and is written in the form

$$\sigma = \sqrt{\sigma_u{}^2 - 2\nu\sigma_{ub} + \nu^2\sigma_b{}^2}$$

is presented in the same article. In the last equality, the values of $\sigma_u{}^2$ σ_{ub}, $\sigma_b{}^2$ can, depending on δ, be determined by table 1.

Table 1. The component values of σ for given value of δ.

δ	$\sigma_b{}^2$	σ_{ub}	σ_u^2
0.1	9.473	22.183	60.508
0.2	4.738	7.374	16.477
0.25	3.735	4.926	10.497
0.3	3.065	3.438	7.186
0.5	1.716	0.936	2.510
0.6	1.373	0.447	1.612
0.7	1.12	0.145	1.447
0.8	0.928	-0.049	1.253
1.0	0.608	-0.257	1.109

For maximum likelihood estimates and complete samples of volume n=8, 10, 12, 15, 18, 20, 25, 30, 40, 50, 75, and 100

[8] presents tables of the values of the function L* as a function of

$$\varepsilon \text{ and } \bar{R} = \exp\{-\exp(-\nu)\}$$

for ε = 0.75, 0.9, 0.95, 0.97, 0.98 and $\bar{R}$ = 0.5(increasing from 0.5 to 0.98 in steps of 0.02).

For the best linear unbiased estimates, the tables of values of the function $L^*(\varepsilon,\nu)$ are presented in [6]. A good log χ^2-approximation for the function $L(\varepsilon,\nu)$ is presented in [9] in the form

$$L(\varepsilon, \nu) = -\ln \frac{m\chi_\varepsilon^2(l)}{l}, \qquad (2.5)$$

where l and m are chosen so that the means and the variations of the quantities $W(\nu)=U-\nu B$ and

$\ln[m\chi^2(l)/l$ - are identical.

Having calculated the estimates $\bar{u}$ and $\bar{b}_i$ by the results of tests of i-th type elements (i=1,...,N), one can write the expression for the lower confidence bound (LCB) of level q for the element's function reliability $R_i(t)$ in the form

$$R_{iq} = L_i^*(q, \bar{\nu}_i), \quad \bar{\nu}_i = \frac{\bar{u} - \ln t}{\bar{b}_i} \qquad (2.6)$$

Therefore, for calculating LCB for function reliability of any type of component (element) with given confidence probability q it is necessary :

- to calculate estimates of the Weibull model's parameters $\bar{u}$ and $\bar{b}$, i = 1, ...N; (using one of the above mentioned methods);
- to calculate the value $\bar{\nu}_i = (\bar{u}_i - \ln t)/\bar{b}_i$ and the value of the function $L_i(q, \bar{\nu}_i)$, as mentioned above;
- to use the expressions (2.3) and (2.6) for given values of confidence probability q.

3. MULTI-VARIATE WEIBULL MODEL

Let us consider a system with a series connection of N components (elements) the failures of which are independent of each other.

If the Weibull model is valid for each of N components, then the function of system reliability R(t) for given (hold fixed) value of time t could be represented as

$$R(t) = \exp\{-\sum_{i=1}^{N}(\frac{t}{\alpha_i})^{\beta_i}\}, \qquad (3.1)$$

or, if we denote $u_i = \ln\alpha_i$ and $b_i = 1/\beta_i$, i = 1, ...N, as

$$R(t) = \prod_{i=1}^{N}\exp\{-\exp(\frac{\ln t - u_i}{b_i})\}, \quad t > 0. \qquad (3.2)$$

Our goal is to give the algorithm for calculating LCB (Low Confidence Bound) $R_q(t)$ with confidence level q for system reliability function R(t) if we have N independent censored

samples

$$t_{(1)}^{(i)} \le t_{(2)}^{(i)} \le \ldots \le t_{(ri)}^{(i)}, \quad i = 1, \ldots N, \; r_i \le n_i, \qquad (3.3)$$

where: n_i is the sample size of component i-th type, r_i is the number of failures of i-th type component.

On the basis of data (3.3) we can calculate the estimations $\bar{u}_i$, $\bar{b}_i$ for unknown parameters u_i and b_i, i=1...N, using one of the methods described in the previous section and it is simple to calculate the point estimation of reliability function as follows:

$$\bar{R}(t) = \prod_{i=1}^{N}\exp\{-\exp(\frac{\ln t - \bar{u}_i}{\bar{b}})\} \qquad (3.4)$$

For calculating LCB $R_q(t)$ of confidence level q (q=0.8-0.95) it is necessary to use the general methodology developed in [1,2,4]. In accordance with [5], the general methodology is necessary to solve the next nonlinear extremal task:

$$R_q(t) = \min_{y \varepsilon S_q} \prod_{i=1}^{N} L_i^* [1 - e^{-y_i}, -\ln\ln(1/\bar{R}')],$$

where

$$S_q = \{y\varepsilon R^N: \; y_i \ge 0; \; \sum y_i = \ln\frac{1}{1-q}\},$$

and $\bar{R}'$ is the value of the statistic $\bar{R}(t)$ determined by expression (3.4) after calculation of the estimates parameters $\bar{u}_i$ and $\bar{b}_i$, i = 1, ... N.

This is denoted by

$$g_i(y_i) = -\ln L_i^*[1 - \exp(-y_i), -\ln\ln(1/\bar{R}'(t))]$$

As is shown in [5, 11], isolate the two situations most frequently encountered in practice, in which the expression for $R_q(t)$ can be written in explicit form.

A. If the functions $g_i(y_i)$ are identical for all i =1...N (which is satisfied when the elements are tested according to the same plan (n, U, r) and estimates of the same type are used for the unknown parameters) and are convex upward on [0, ln1/(1-q)], then

$$R_q(t) = \{L^*[1 - (1 - q)^{1/N}, \quad -\ln\ln(1/\bar{R}'(t))]\}^N \qquad (3.5)$$

B. If all the functions $g_i(y_i)$ are convex downward on [0, ln1/(1-q)], then

$$R_q(t) = \min_{1\le i\le N} L_i^*[q, -\ln\ln(1/\bar{R}'(t))] \qquad (3.6)$$

where, as also was mentioned above, $\bar{R}'(t)$ is the observed value of statistic $\bar{R}(t)$ determined by expression (3.4).

If the convexity conditions are not satisfied for the functions $g_i(y_i)$ on the interval $[0, \ln 1/(1-q)]$, then they can be replaced by convex approximations $\bar{g}_i(y_i)$ such that the error Δ of formula (3.6) is no greater than

$$\Delta^* = \exp(-\sum_{i=1}^{N} \Delta_i)$$

where

$$\Delta_I = \max_y | \bar{g}_i(y) - g_i(y) |, i = 1 \ldots N.$$

Our calculation investigations showed that most practical situations (that is, for components having a very high level of reliability and relatively small sample sizes) take place in case B. Calculation of LCB by use of formula (3.6) involves calculating of the point estimation of system reliability $\bar{R}(t)$ and then subsequently calculating LCB of level q for reliability functions of each component of N systems and choosing the minimal value for them.

As a corollary of result B it is not difficult to get the following expression for LCB $R_q(t)$, if all components of the system have identical (or almost identical) rate of censoring, that is, $\delta_i = r/n_i = \text{const.}, i=1,\ldots N$:

$$R_q(t) = L_0^*[q, -\ln\ln(1/\bar{R}'(t)], \qquad (3.7)$$

where

$L_0^*[q, -\ln\ln(1/\bar{R}'(t)]$ is that function from $L_i^*[q, -\ln\ln(1/\bar{R}(t)]$, which corresponds to minimal sample size (that is, sample size $n_0 = \min(n_i)$).

4. ILLUSTRATIVE EXAMPLES.

Example 1. In order to find the value of the LCB of level q=0.9 for the reliability function of the system that consists of N=3 components, the life time of each has a Weibull distribution with unknown parameters. The components were tested according to the plans (n_i, U, r_i), i=1,2,3, that is, n_i specimens of type i are tested until r_i failures appear and the failure specimens are permanent.

For this example given the following values of the operating times until failure (in hours) the following results were obtained:

t_1=1820, t_2=1960, t_3=2172 (for specimens type 1);

t_1=2441, t_2=2841, t_3=3432, t_4=3824 (for specimens type 2);

t_1=5329, t_2=5682, t_3=7016, t_4=7919, t_5=9566, t_6=11760 (for specimens type 3).

On the basis of this data the estimates of the unknown parameters found by the method proposed in [9] (that is, maximum likelihood estimates) are:

$\bar{u}_1 = 7.62$, $\bar{b}_1 = 0.13$, $\bar{u}_2 = 8.13$, $\bar{b}_2 = 0.21$, $\bar{u}_3 = 8.46$, $\bar{b}_3 = 0.38$

Using the expression (3.4) we can calculate the point estimate for reliability function R(t) as the product of the corresponding point estimates of component's reliability functions (for t = T_0=1000):

$$\bar{R} = \bar{R}_1 * \bar{R}_2 * \bar{R}_3 = 0.996*0.997*0.983 = 0.976$$

To calculate LCB of level q for system reliability R(t) it is necessary (in a general case) to calculate LCB at the same level q for each system's component assuming that the point estimate of the reliability function of this component is identical to the point estimate reliability function system, that is, to $\bar{R}'(t)$. But in this particular case ($\delta_1=\delta_2=\delta_3=0.5$) we can use formula (3.7), according to which it is sufficient to calculate LCB only for the component with smallest sample size, that is, for 1-st component because $n_1=6=\min\{6, 8, 12\}$.

First of all we have to determine the value of function L(q, v), where $\nu = -\ln\ln \bar{R}' = 3.72$. Since we used the maximum likelihood estimates for parameters u_i and b_i, now we need to use the tables from [8]. But for more visualization we will use the normal approximation of function L(q, v) by formula (2.4), although it gives the same uncontrollable error.

From table 1 we can find out the values σ_b^2, σ_{ub} *and* σ_u^2, corresponding to δ=0.5 and then calculate $\sigma = (\sigma_u^2 - 2\nu\sigma_{ub} + \nu^2\sigma_b^2)^{1/2} = 4.39$ using formula (2.4) which gives the following result (since z_q = 1.28 when q = 9):

$$L(q, \nu) \approx 3.72 - 1.28 * 4.39 / \sqrt{6} = 1.424$$

and formula (2.3) gives

$$L^*(q, \nu) = \exp\{-\exp(-L(q, \nu))\} = 0.786$$

that is, the final answer according to formula (3.7) is R_q = 0.786

For comparison we can calculate LCB of level q=0.9 for each component mentioned above. We obtain the following results:

$$R_{1q} = 0.873, \; R_{2q} = 0.93, \; R_{3q} = 0.904$$

Note, that if we multiply these LCB's then we will get only the value 0.73, that is essentially lower.

Remember, that calculation of LCB for the system reliability function requires calculating the conditional LCB R_{iq}^* for each component's reliability function assuming that the point estimate of the component's reliability function is identical to the point estimation of system $\bar{R}'$. Corresponding calculations give the following result:

$$R_{1q} = 0.786, \; R_{2q}^* = 0.838, \; R_{3q} = 0.884.$$

As we can see, the smallest of these values determine the LCB for system reliability function which we have obtained above:

$$R_q = R_{1q}^* = 0.786$$

Example 2. Note, that $\min(R_{iq}^*)$ does not always fall on the component that has the smallest sample size as obtained in previous example 1.

Let us change the initial data in example 1 slightly. For example, let us exchange only the values n_1=6 and n_3=12, that is, let n_1=12 and n_3=6 but the test results of all the components allowed have the same estimate parameters u_i and b_i, i = 1, 2, 3.

It is not difficult to ensure that calculations that were mentioned above will give the following results.

1.The values of conditional LCB's for all components (of the same level q = 0.9) are:

$$R_{1q}^* = 0.855,\ R_{2q}^* = 0.838,\ R_{3q}^* = 0.868.$$

that is, the smallest value of the conditional LCB falls onto the component #2, that has sample size n_2=8 (not smallest!) and therefore the LCB of the system reliability function

$$R_q = R_{2q}^* = 0.838$$

2. The values of LCB's for all components (of level q = 0.9) are:

$$R_{1q} = 0.914,\ R_{2q} = 0.93,\ R_{3q} = 0.89.$$

and the product of these values (sometimes used for calculating LCB for system reliability function) gives us the value 0.75. This is much less than 0.838, which we obtained by the method suggested in this paper.

5. CONCLUSIONS.

The methodology developed allows the prediction of system reliability in which components are subjected to different types of the physics-of-degradation process during the service life, because for every type of degradation there is a separate Weibull model.

The value of this methodology is that it allows the prediction of the LCB of a system reliability function after testing a few samples of each component of this system during a relatively short period of time. In addition it allows us to predict the system reliability at the beginning of development when the testing of the system as a whole either has high cost or may be impossible in a short period of time.

Moreover, we may use this methodology even when the Accelerated Life Testing of each system's components is known. In this case we have to transform the testing results during ALT to the equivalent testing results corresponding to ordinary conditions. For this transformation one can use the standard methods.

The time of the testing period is determined by ALT longevity for the system components and can be made sufficiently small in principle. For instance, if we could provide by Accelerated Life Testing each component in our example 1 the acceleration coefficient K equal to about 10 (it is a realistic possibility), then we could have obtained the confidence estimate of system reliability function during the request operating time of our system only on the basis of test results its components. Therefore, we have the possibility of decreasing the time (and consequently, the cost) of new system development.

In this paper only series systems are considered, but the proposed methodology can be extended also to the systems with arbitrarily series-parallel structures.

The proposed methodology also allows combining of in-service life data with results of ALT. This methodology is especially important for reducing cost and time, and improving of quality of new product development.

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