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Abstract—This paper proposes a new scheme for constructing software reliability growth models (SRGM) based on a nonhomogeneous Poisson process (NHPP). The main focus is to provide an efficient parametric decomposition method for software reliability modeling, which considers both testing efforts and fault detection rates (FDR). In general, the software fault detection/removal mechanisms depend on previously detected/removed faults and on how testing efforts are used. From practical field studies, it is likely that we can estimate the testing efforts consumption pattern and predict the trends of FDR. A set of time-variable, testing-effort-based FDR models were developed that have the inherent flexibility of capturing a wide range of possible fault detection trends: increasing, decreasing, and constant. This scheme has a flexible structure and can model a wide spectrum of software development environments, considering various testing efforts. The paper describes the FDR, which can be obtained from historical records of previous releases or other similar software projects, and incorporates the related testing activities into this new modeling approach. The applicability of our model and the related parametric decomposition methods are demonstrated through several real data sets from various software projects. The evaluation results show that the proposed framework to incorporate testing efforts and FDR for SRGM has a reasonably accurate prediction capability and it depicts the real-life situation more faithfully. This technique can be applied to a wide range of software systems.

Index Terms—Fault detection, nonhomogeneous Poisson process (NHPP), software faults and failures, software reliability growth model (SRGM), testing-effort functions.

I. INTRODUCTION

Due to the rapid development of computer and information technology, society increasingly depends on software-intensive systems. Software is embedded in many modern systems, including expensive scientific computing systems, financial banking systems, industrial applications, university computer centers, and home personal computers. Since the demands for complex and large-scale software systems are increasing more rapidly, the possibility of programmers’ design errors in the systems will grow appreciably. Consequently, the possibility of crises due to software failures will continue to increase. These failures can generate enormous losses of revenue for many enterprises. Therefore, to determine system reliability, the software reliability must be carefully evaluated.

Software reliability is similar to hardware reliability because both can be described by probability distributions. However, software faults are harder to visualize, detect, and correct, compared with physical hardware faults. The reliability of any system depends on the correctness of the system design,
the correctness of the mapping of the system design to implementation, and the reliability of the system-components. Software systems are quite different from hardware systems because the former do not wear out, at least in a physical sense. Therefore, fault and failure patterns for software and hardware are different, and the difference is fundamental. Thus, the same models used for measuring hardware reliability cannot be used for measuring software reliability.

Hardware has mixtures of decreasing and increasing failure rates [1], [2]. The decreasing failure rate is caused by repairing original design-related hardware failures. The increasing failure rate is due to hardware component aging or wear-out. On the other hand, software systems usually have a decreasing failure rate [1]–[3]. And there is some confusion as to whether software reliability is probabilistic or deterministic. The answer depends on how we view software reliability. However, software has to be considered with its environment. Various software reliability measurement indicate different values for the same software under different testing/operating environments. According to the ANSI definition [4]: “Software reliability is the probability of failure-free software operation for a specified period of time in a specified environment.” Hence, accurately modeling software reliability, and predicting its possible trends, are essential in determining the system reliability. To achieve a highly reliable software system, many software fault detection/removal techniques can be used by the program developers or testing teams. In applying these techniques, the SRGM are important, because they can provide quite useful information for developers and testers during the testing/debugging phase.

Numerous fault-prediction models are published, and many efforts were made to estimate software reliability from real DS. Most of them are based on

- calendar-time, e.g., the Jelinski–Moranda Model [4],
- staff-time, e.g., Shooman Model [4], or
- computer-time, e.g., Musa Model [4], [5].

Musa [5], [6] first discussed the validity of execution-time theory by taking DS from real software systems. However, most existing DS are not based on the execution-time concept. Recently, [1]–[3] and [7]–[9] proposed two simple SRGM with Weibull-type and logistic TE functions, respectively. These models attempt to account for the relationship among the calendar testing, the amount of TE, and the number of software faults detected during testing. The TE can be measured by the human power, the number of test cases, the number of CPU hours, etc. When applied extensively to real software development projects, these models provide a reasonable fit to the observed data and give insightful interpretations for the resource consumption process during the software development phase [7]–[9].

In general, among various SRGM, two most important factors affect reliability: the number of initial faults and the FDR. The number of initial faults is the number of faults in the software at the beginning of the test. This number is usually a representative measure of software reliability. Knowing the number of residual faults can help to determine whether the software is suitable for customers to use or not, and how much more testing resources are required. It can provide an estimate of the number of failures that will eventually be encountered by the customers. The FDR, on the other hand is used to measure the effectiveness of fault detection by test techniques and test cases. In the vast literature [1]–[6], and [10]–[19], most researchers assume a constant FDR per fault in deriving their SRGM. That is, they assume that all faults have equal probability of being detected during the software testing process, and the rate remains constant over the intervals between fault occurrences.

In reality, the FDR strongly depends on the skill of test teams, program size, and software testability. Through real data experiments and analyzes on several software development projects [20], the FDR has 3 possible trends as time progresses: increasing, decreasing, or constant. We thus treat the FDR as a function of time to interpret these possible trends; viz, we assume a time-variable fault detection function. And, we consolidate these 2 concepts, TE function and time-variable FDR, into a combined analysis for software reliability modeling.

This paper estimates the SRGM parameters by MLE and LSE methods. We take the estimated parameters into the proposed software-fault prediction model and compare the predicted results with other existing SRGM. From the comparison results, our analysis determines the reasons why the predicted results agree or disagree with the actual results. Experimental results show that the combined model gives a more accurate prediction, and depicts the real-life situation more faithfully.

Section II describes a basic SRGM that combines the TE function and the time-variable FDR.

Section III extends the basic SRGM to consider various time-dependent FDR, and discusses several modeling propositions.

Section IV estimates these parameters of the proposed SRGM based on the actual observed software failure data, plots their mean value functions, and fairly compares them with other existing models.

Section V discusses FDR and the reliability trend.

II. TE-BASED SOFTWARE RELIABILITY MODELING

The mathematical expression of TE-based is:

\[
\frac{dm(t)}{dt} = \frac{1}{w(t)} \cdot \frac{1}{r(t)} \cdot [a - m(t)], \quad a \geq 0, \quad 0 < r(t) < 1
\]

This basic SRGM (1) is based on the assumptions:

1) The fault removal process is NHPP.
2) The software system is subject to failures at random times caused by the manifestation of remaining faults in the system.
3) The mean number of faults detected in \((t, t + \Delta t)\), \(dm(t)/dt\) by the current \(w(t)\), is proportional to the mean number of remaining faults in the system.
4) The \(r(t)\) is a function of time (not just a constant).
5) The time-dependent behavior of TE can be modeled by a Logistic or a Weibull distribution.
6) Each time a failure occurs, the fault that caused it is immediately and perfectly removed, and no new faults are introduced.
7) Correction of errors takes only negligible time and a
detected error is removed with certainty.

Eq. (1) has 2 elements which influence the number of faults
detected: \( w(t) \) and \( r(t) \). If \( r(t) \) is constant over time, then

\[
\frac{dm(t)}{dt} = w(t) \cdot r \cdot [a - m(t)],
\]

Solve (2) using the boundary condition \( m(0) = 0 \):

\[
m(t) = a \cdot [1 - \exp(-r \cdot [w(t) - w(0)])].
\]

A. The TE Function

The first component in (1) is the TE function. During the soft-
ware testing/debugging phase, appreciable TE, e.g., number of
test cases, human Power, and CPU time, is consumed. The con-
sumed TE can indicate how effective software faults are de-
tected. Hence, resource consumption or allocation of human
power can be modeled by various distributions. From the studies
in [1]–[3], [7]–[9], [20], [21], several TE pattern expressions
exist, as shown in this Section II-A.

1) Constant TE Consumption: In the derivation of classical
SRGM [4]–[6], [11]–[14], [17], [22], most researchers assumed
that the TE (workload) of a software system is constant:

\[
w(t) = w_0.
\]

2) Weibull-Type TE Function: According to [1]–[3], [5],
[23], TE should not be assumed constant throughout the testing
phase. In fact, instantaneous TE ultimately decreases during
the testing life cycle so that the cumulative TE approaches a
finite limit. This analysis is reasonable because no software
company will spend infinite resources on software testing. Thus we describe TE a Weibull distribution:

\[
W(t) = N \cdot \left[1 - \exp \left(- \int_0^t g(\tau) \, d\tau \right)\right]
\]

\[
W(t) \equiv \int_0^t w(\tau) \, d\tau.
\]

There are 3 cases.

1) \( g(t) = \beta. \) Then \( w(t) \equiv N \cdot \beta \cdot \exp(-\beta \cdot t). \) There is an
exponential curve, and the cumulative TE in \((0, t]\) is

\[
W(t) = N \cdot [1 - \exp(-\beta \cdot t)].
\]

2) \( g(t) = \beta \cdot t. \) Then

\[
w(t) = N \cdot \beta \cdot t \cdot \exp \left[-\frac{\beta}{2} \cdot t^2\right].
\]

There is a Rayleigh curve and the cumulative TE is

\[
W(t) = N \cdot \left(1 - \exp \left[-\frac{\beta}{2} \cdot t^2\right]\right).
\]

3) \( w(t) = N \cdot \beta \cdot m \cdot t^{m-1} \cdot \exp(-\beta \cdot t^m). \) There is a Weibull
curve, and the cumulative TE is

\[
W(t) = N \cdot (1 - \exp[\beta \cdot t^m]),
\]

\[
m_j \equiv \text{total number of faults detected by } t_j.
\]

B. The FDR

The second component in (1) is the FDR: the rate of discov-
ering new faults in software during the testing phase. Typically,
whether the software faults can be detected or not, depends on
the ability of programmers/debuggers, the software structure,
the maturity of software development procedure, and the corre-
lation among program modules.

1) Constant Proportionality: Most existing SRGM assume
that the mean number of faults detected in \( t \) is pro-
portional to the number of remaining faults [4], [11]–[14], [17],
[22]:

\[
m(t + \Delta t) = r \cdot w(t) \cdot [a - m(t)] \cdot \Delta t,
\]

\( r \) is a constant proportionality.

2) Time-Variable FDR: In our experiments, the FDR is mea-
sured by the “average number of faults detected per TE expen-
diture” or by the “number of faults detected by special checking
activities.” This information is helpful for the system de-
velopers to plan the checking activities, diagnose problems, and
assess the effects of changes. And, it indicates cost-effective-
ness of various checking activities in the long run. To inter-
pret the possible variation in FDR with time, we survey some
real test/debugging DS [4], [5], [11], [12], [15], [17], [18], [22],
[25]–[27]. We analyze those fault-detection processes and ob-
serve various fault-detection behaviors. Most of the grouped DS
have the form:

\[(t_0, m_0), (t_1, m_1), \ldots, (t_n, m_n);\]
Generally speaking, the data obtained based on calendar time tends to be noisy (short-term randomness) and might not comply with most assumptions for existing SRGM [4], [5], [28]. One way of interpreting FDR at various times is to use the computation approach in [28]. From (3), and using \( m(t_i), m(t_{i+1}) \), the FDR between \( t_i \) and \( t_{i+1} \) is estimated by:

\[
\frac{m(t_i)}{m(t_{i+1})} = \frac{a \cdot [1 - \exp(-r \cdot \Delta W(t_i))]}{a \cdot [1 - \exp(-r \cdot \Delta W(t_{i+1}))]},
\]

or

\[
m(t_i) \cdot [1 - \exp(-r \cdot \Delta W(t_{i+1}))] - m(t_{i+1}) \cdot [1 - \exp(-r \cdot \Delta W(t_i))] = 0.
\]

Eq. (14) is solved numerically [29] (usually on a computer). Fig. 1 shows that the FDR varies with time for various real DS:

- Fig. 1(a), (e), (f), (j), (n) show that FDR has an increasing trend as time progresses;
- Fig. 1(b)–(d), (g), (k), (m) show that FDR is nonincreasing over time \( t \);
- Fig. 1(h), (i), (l) show that FDR seems to be a constant.

There are some peaks and valleys in describing the possible FDR states. This might be due to sudden changes of test schemes, test teams, or the software under test.

A software testing process consists of several testing stages, including unit testing, integration testing, system testing, and...
installation testing. If the software system is very large and complex, programmers can usually remove the easy-to-detect faults in their programs through inspection at the early stage of software testing. As time passes, the testing phase proceeds to the integration testing and the system testing phases, and it becomes more difficult for the programmers to detect the remaining faults. In this case, initially FDR is increasing and then it is decreasing [see Fig. 1(b), (k), or (m)]. In other words, the length of time between fault-detection will increase. On the other hand, if the software are not large and do not have many program modules, then the testing skills of programmers will improve as time progresses, and more efficient testing schemes can be conducted. Accordingly, the FDR can have an increasing trend [see Fig. 1(f), (j), or (n)]. If the requirements are changed and new features are added, or if new faults are introduced during debugging, the FDR will also increase. In any case, the FDR has three possible trends as time progresses: increasing, decreasing, and constant, as shown in the real project data. Section III discusses software reliability modeling for various FDR.

III. INVESTIGATION ON FDR

We examine specific expressions of FDR and make several propositions. Because the fault-detection task is performed by programmers after coding, they will analyze the source-code or the results from object-code executions. Section II-B-2 suggests that a time-dependent coefficient can replace the constant FDR assumption [20]. To interpret the results, we assume that the FDR is a function of the number of initial faults, the number of detected faults, and the FDR. By re-arranging (1), the FDR per remaining fault at testing time $t$ can be described. This represents the detectability of a fault for the current fault content [3], [17], [36]:

$$d(t) = \frac{dm(t)}{dt} \cdot \frac{1}{a - m(t)} = r(t) \cdot w(t),$$

i.e.,

$$r(t) = \frac{d(t)}{w(t)},$$

Eq. (15) implies that $d(t) \propto r(t)$: $r(t) \uparrow$, $d(t) \uparrow$ and $r(t) \downarrow$, $d(t) \downarrow$; and implies that the FDR per remaining fault is a function of the current $w(t)$. We view $d(t)$ as a software reliability-growth index. Most software reliability models assume that $w(t)$ is constant (some do not even consider it, and they set $r$ as a constant rate [4], [5], [11]–[13]). For $w(t) = constant$, then $d(t) = constant$, which indicates that these models have a homogeneous FDR. In the real projects, however, (15) gives a more precise description about the behavior of $d(t)$. Several scenarios are discussed in Sections III-A–III-C.

A. Proposition 1: Constant FDR for $r(t)$

If $r(t)$ is constant in $t$, then $m(t)$ is a constant FDR. 

Case 1:

$$r(t) = r.$$

Eq. (16) shows that all faults are equally detectable during testing. Under this assumption, the FDR per unit TE is constant. Substitute (16) into (1) and solve the differential equation under the boundary condition. $m(0) = 0$ [8], [9]:

$$m(t) = a \cdot [1 - \exp(-r \cdot \Delta W(t))].$$

From (15), the FDR per remaining fault at testing time $t$ is

$$d(t) = r \cdot w(t).$$

Eq. (18) indicates that $d(t)$ is dominated by $w(t)$, whether $d(t)$ is homogeneous or nonhomogeneous.

B. Proposition 2: Non-Decreasing $r(t)$

If $r(t)$ is nondecreasing in $t$, then $m(t)$ is an increasing fault detection function.

Case 2.1:

$$r(t) = r(0) + k \cdot \frac{m(t)}{a}, \quad k > 0.$$  

Under this assumption, we use a linear model to describe the FDR. In (19), $r_0$ is the initial FDR and $k$ is the slope (model parameter) which can be estimated by LSE. The $k$ is used to track and predict the increasing FDR trends. Substitute (19) into (1), and solve the differential equation:

$$m(t) = a \cdot \left(1 - \frac{r_0 + k}{r_0 \cdot \exp[(r_0 + k) \cdot \Delta W(t)] + k}\right).$$

From (15), the FDR per remaining fault is

$$f(t) = w(t) \cdot \left(1 - \frac{k}{\exp[(r_0 + k) \cdot \Delta W(t)] + k}\right),$$

and is monotonically increasing with time $t$. That is, (21) implies that (20) describes a fault-detection process in which the detectability of a fault increases with the progress of software testing.

Case 2.2:

$$r(t) = r_0 + (r_f - r_0) \cdot \frac{m(t)}{a}, \quad 0 < r_0 < r_f.$$  

Substitute (22) into (1); the result is a Riccati differential equation with solution:

$$m(t) = a \cdot \left(1 - \frac{r_f}{r_0 \cdot \exp[r_f \cdot \Delta W(t)] + r_f - r_0}\right), \quad 0 < r_0 < r_f.$$  

Similarly, from (15), the FDR per remaining fault at testing time $t$ is

$$d(t) = w(t) \cdot r_f \cdot \left(1 - \frac{r_f - r_0}{r_0 \cdot \exp[r_f \cdot \Delta W(t)] + r_f - r_0}\right), \quad 0 < r_0 < r_f$$

which is monotonically increasing. Similarly, (24) means that (23) describes a fault-detection process in which the detectability of a fault increases with the progress of software testing.

C. Proposition 3: Non-Increasing $r(t)$

If $r(t)$ is nonincreasing with time $t$, then $m(t)$ is a decreasing FDR function. This case describes the situation that many easy faults are effectively detected in the beginning and the last few faults are more difficult to detect.

Case 3.1:

$$r(t) = r_0 \cdot \left(1 - \frac{m(t)}{a}\right).$$
Substitute (25) into (1); the solution is:

\[ m(t) = a \cdot \left( 1 - \frac{1}{r_0 \cdot \Delta W(t) + 1} \right), \quad 0 < r_0 < r_f. \tag{26} \]

From (15), the FDR per remaining fault at test time is

\[ d(t) = \frac{\frac{r_0 \cdot w(t)}{r_0 \cdot \Delta W(t) + 1}}. \tag{27} \]

Case 3.2:

\[ r(t) = r_0 + k \cdot \frac{m(t)}{a}, \quad k < 0. \tag{28} \]

Substitute (28) into (1), the solution is:

\[ m(t) = a \cdot \left( 1 - \frac{r_0 + k}{r_0 \cdot \exp((r_0 + k) \cdot \Delta W(t)) + k} \right). \tag{29} \]

From (15), the FDR per remaining fault at test time is

\[ d(t) = w(t) \cdot \left( 1 - \frac{k}{\exp((r_0 + k) \cdot \Delta W(t)) + k} \right). \tag{30} \]

Case 3.3:

\[ r(t) = r_0 + (r_f - r_0) \cdot \frac{m(t)}{a}, \quad r_0 < r_f. \tag{31} \]

Substitute (31) into (1), the solution is:

\[ m(t) = a \cdot \left( 1 - \frac{r_f}{r_0 \cdot \exp([r_f] \cdot \Delta W(t)) + r_f - r_0}, \quad r_0 > r_f. \tag{32} \]

From (15), the FDR per remaining fault at test time is

\[ d(t) = w(t) \cdot r_f \cdot \left( 1 - \frac{k}{r_0 \cdot \exp([r_f] \cdot \Delta W(t)) + r_f - r_0} \right). \tag{33} \]

D. Model Classification

Table I divides the propositions in Sections III-A–III-C into 4 groups.

Various TE functions can be applied in each of these 4 groups to form a particular software reliability model. Consider 4 TE functions: Logistic, Weibull, Rayleigh, and Exponential; then there is a maximum of 16 models based on our approach.

IV. EXPERIMENTAL STUDIES AND RESULTS

To check the performance of our models in Section III, and to make a fair comparison with other existing SRGM, we apply 3 DS to our models. These DS are in Table II. The 2 comparison criteria for evaluations among accepted models are:

1) \( AE \) [5], [8], [10], [14]

\[ AE = \frac{|M_a - a|}{M_a}. \tag{34} \]

2) MSF

\[ MSF = \frac{1}{k} \sum_{i=1}^{k} [m(t_i) - m_i]^2. \tag{35} \]

A smaller MSF indicates a smaller fitting error and better performance.

Other useful quantitative measures to assist in determining the number of residual faults and the probability that a software system can survive up to a certain time, are:

1) \( MF \) (maximum faults): total number of initial faults, \( n(\infty) \);

2) \( RF \) (remaining faults in the system at test time): \( m(\infty) - m(t) \), an important indicator of software reliability and a useful measure for planning maintenance activities;

3) \( MTTF \) (mean time to failure);

4) \( SR \) (software reliability) [8], [9], [19], [30].

A. DS #1

The system is a PL/I database application software. The \( \alpha, \beta, m \) of the Weibull-type TE function in (7)–(9), and \( N, A, \alpha \) of the Logistic TE function in (10) can be derived using MLE and LSE. Similarly, \( a, r_0, r_f, k \) of the mean value function can also be solved numerically. Fig. 2 shows the fitting of the estimated TE by using (7)–(10). Table III summarizes the estimated parameters for various TE functions, mean value function, and the comparison criteria. Our proposed software reliability growth function fits pretty well at the 5% -significance level through the K–S goodness-of-fit [4]. From Table III, both MSF and AE in group B are less than those in other groups and the existing SRGM; therefore, group B could have a better goodness-of-fit. This performance improvement is achieved by the using 2 parameters to interpret the FDR patterns instead of the traditional assumption of constant FDR.

By adding an extra parameter in modeling the fault detection phenomenon, the estimation becomes more tedious because more numerical calculations are involved. However, the additional calculations can be fully automated. If high reliability is
TABLE II
SUMMARY OF REAL DS THAT WERE STUDIED

<table>
<thead>
<tr>
<th>DS</th>
<th>NFD</th>
<th>Observation Period</th>
<th>Software Project/Program Descriptions and Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>328</td>
<td>PL/I application Program, Execution Time: 47.65 CPU hours, Software Size: 1317k LOC</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>86</td>
<td>Execution Time: 93 CPU hours</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>136</td>
<td>Real-time Command &amp; Control Application (System T1), Execution Time: 25.3 CPU hours, 9 Programmers, Software Size: 21.7k LOC</td>
</tr>
</tbody>
</table>

TABLE III
SUMMARY OF MODEL PARAMETERS AND COMPARISONS FOR DS #1

<table>
<thead>
<tr>
<th>Model (Group A)</th>
<th>α</th>
<th>r</th>
<th>MSF</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>394.076</td>
<td>0.0427223</td>
<td>118.29</td>
<td>10.07</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>565.35</td>
<td>0.0196597</td>
<td>122.09</td>
<td>57.91</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>459.08</td>
<td>0.0273367</td>
<td>268.42</td>
<td>28.23</td>
</tr>
<tr>
<td>with Exponential function</td>
<td>628.252</td>
<td>0.0117836</td>
<td>140.66</td>
<td>131.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group B)</th>
<th>α</th>
<th>r₀</th>
<th>rₖ</th>
<th>MSF</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>337.41</td>
<td>0.018962</td>
<td>0.113343</td>
<td>163.095</td>
<td>5.75</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>545.686</td>
<td>0.0125642</td>
<td>0.109649</td>
<td>91.0226</td>
<td>3.43</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>371.438</td>
<td>0.0137198</td>
<td>0.0805023</td>
<td>158.918</td>
<td>3.75</td>
</tr>
<tr>
<td>with Exponential function</td>
<td>352.521</td>
<td>0.0108438</td>
<td>0.108197</td>
<td>83.9989</td>
<td>1.53</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group C)</th>
<th>α</th>
<th>r₀</th>
<th>k</th>
<th>MSF</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>430.662</td>
<td>0.0409427</td>
<td>-0.0146536</td>
<td>103.0326</td>
<td>20.11</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>385.392</td>
<td>0.0229036</td>
<td>0.0393828</td>
<td>87.5831</td>
<td>6.65</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>379.947</td>
<td>0.0239060</td>
<td>0.0385439</td>
<td>406.7115</td>
<td>6.15</td>
</tr>
<tr>
<td>with Exponential function</td>
<td>385.179</td>
<td>0.0180857</td>
<td>0.0547021</td>
<td>83.3452</td>
<td>7.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group D)</th>
<th>α</th>
<th>r₀</th>
<th>MSF</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>582.538</td>
<td>0.0308452</td>
<td>96.9921</td>
<td>62.72</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>958.718</td>
<td>0.0118215</td>
<td>124.3994</td>
<td>167.79</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>702.693</td>
<td>0.0191208</td>
<td>247.84</td>
<td>96.09</td>
</tr>
<tr>
<td>with Exponential function</td>
<td>1225.66</td>
<td>0.0082272</td>
<td>169.7194</td>
<td>242.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Existing SRGM</th>
<th>α</th>
<th>r</th>
<th>MSF</th>
<th>AE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-O Model</td>
<td>760.0</td>
<td>0.0322688</td>
<td>139.815</td>
<td>112.29</td>
</tr>
<tr>
<td>Inflexion S-Shaped Model</td>
<td>389.1</td>
<td>0.0935493</td>
<td>133.53</td>
<td>8.69</td>
</tr>
<tr>
<td>Delayed S-Shaped Model</td>
<td>374.05</td>
<td>0.197651</td>
<td>168.67</td>
<td>4.48</td>
</tr>
<tr>
<td>Exponential Model</td>
<td>455.371</td>
<td>0.0267306</td>
<td>205.93</td>
<td>27.09</td>
</tr>
<tr>
<td>HGDM</td>
<td>387.71</td>
<td>*</td>
<td>138.12</td>
<td>8.30</td>
</tr>
</tbody>
</table>

Fig. 2. Observed/estimated TE vs time, for DS #1.

required in some critical applications, such as large-scale commercial software or safety-critical flight software, the cost of extra computation for more accuracy is easily justified. From our simulations, the continuous curve of an estimated mean value function has an inflection point; i.e., it has S-shaped behavior due to $r_f > r_0$ in group B of Table III. The derived software reliability model under such an assumption, (22), was used [11], [12], [14], [20]. In summary, the combined model (group B) that incorporates the TE function and time-variable FDR, actually fits the DS satisfactorily in this experiment.

B. DS #2
This is the pattern of discovery of faults [27]. The cumulative number of discovered faults up to 22 days is 86 and the total consumed debugging time is 93 CPU hours. All debugging data are used in this experiment. Each parameter is estimated by MLE and LSE in the proposed SRGM, shown in Table IV. Fig. 3 fits the estimated TE by using (8)–(10). Table IV shows that the MSF for groups C and D are less than those of other groups and existing SRGM. The continuous curves for the estimated mean value function have an inflection point, showing S-shaped behavior due to $r_f > r_0$. In summary, the combined model (group C or D) of incorporating TE function and time-variable fault detection fits this DS better than others.

C. DS #3
This is the System T1 data of the US Rome Air Development Center (RADC) projects in [5], [6], [25]. The number of
TABLE IV
SUMMARY OF MODEL PARAMETERS AND COMPARISONS FOR DS #2

<table>
<thead>
<tr>
<th>Model (Group A)</th>
<th>α</th>
<th>r</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>88.853</td>
<td>0.039059</td>
<td>25.2279</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>87.0318</td>
<td>0.0345417</td>
<td>7.772</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>88.1616</td>
<td>0.0359624</td>
<td>3.91643</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group B)</th>
<th>α</th>
<th>r₀</th>
<th>r_f</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>89.4528</td>
<td>0.184849</td>
<td>0.0543846</td>
<td>14.05903</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>87.3126</td>
<td>0.017449</td>
<td>0.0522558</td>
<td>18.906772</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>87.3472</td>
<td>0.0177506</td>
<td>0.0015699</td>
<td>20.4568</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group C)</th>
<th>α</th>
<th>r₀</th>
<th>k</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>97.5332</td>
<td>0.0472247</td>
<td>-0.0355523</td>
<td>7.554563</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>97.6841</td>
<td>0.0360078</td>
<td>-0.0227224</td>
<td>6.5909</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>112.182</td>
<td>0.0335812</td>
<td>-0.0335811</td>
<td>6.61018</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (Group D)</th>
<th>α</th>
<th>r₀</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Logistic function</td>
<td>106.10</td>
<td>0.0437178</td>
<td>7.33727</td>
</tr>
<tr>
<td>with Weibull function</td>
<td>114.92</td>
<td>0.0314776</td>
<td>6.96331</td>
</tr>
<tr>
<td>with Rayleigh function</td>
<td>112.183</td>
<td>0.0335812</td>
<td>6.61018</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Existing SRGM</th>
<th>α</th>
<th>r</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-O Model</td>
<td>137.072</td>
<td>0.0515445</td>
<td>25.33</td>
</tr>
<tr>
<td>Delayed S-Shaped Model</td>
<td>88.033</td>
<td>0.228148</td>
<td>6.31268</td>
</tr>
<tr>
<td>HGD Model</td>
<td>88.30</td>
<td>*</td>
<td>33.6812</td>
</tr>
</tbody>
</table>

V. FDR AND RELIABILITY TREND

Software reliability studies are usually based on the application of several SRGM to obtain various measures of interest. Reliability growth can be analyzed by trend tests. Blindly applying SRGM might not lead to meaningful results when the trend indicated by the data differs from that predicted by the model. If the model is applied to the data and shows a trend in accordance with its assumption, the results can be greatly improved [4], [5], [31]–[34]. Various statistical tests have been published (such as Kendall, Spearman or Laplace test) for identifying trends in grouped data or time-series. The Laplace test is very useful in determining the software reliability growth, and has excellent performance for NHPP. We calculate the Laplace trend factor \( U(t) \) [31]–[33]. A negative \( U(t) \) indicates a decreasing failure intensity, and thus, reliability growth. On the other hand, a positive \( U(t) \) indicates an increasing failure intensity, and thus the reliability decreases. If \(-2 \leq U(t) \leq 2\), then it indicates a stable reliability [4], [5], [31]–[34].

Using DS #1, Fig. 5 shows the Laplace trend test results. It shows that the trend test applied to this DS indicates a reliability growth. Thus, in this case our models can be applied. To illustrate, we only use Logistic TE function as the estimated value functions. Similar analyzes and discussions can be applied to the other TE functions or the other DS. The capability of the
Fig. 6. Relative error curves for various SRGM, based on DS #1. (a), (b), (c), (d) depict the model with Logistic function in groups A, B, C, D, respectively. (e) is the G-O model; (f) is the Yamada S-shaped model.

model to predict failure behavior from present and past failure behavior is predictive validity [4]–[6], which can be represented by computing the RE for a DS:

\[
RE = \frac{m(t_q) - q}{q}.
\]

If \( q \) failures are observed by \( t_q \), we use the failure data up to time \( t_e \) (\( t_e \leq t_q \)) to estimate the parameters of \( m(t) \). Substituting the estimates of these parameters in the mean value function yields the estimate of the number of failures \( m(t_q) \) by \( t_q \). The estimate is compared with \( q \). The procedure is repeated for various values of \( t_e \) [5]. We can check the predictive validity by plotting the relative error vs \( t_q \). Following [5] and using the real project failure data in Section IV-A, compute the relative error in prediction for the DS at the end of testing. Fig. 6 shows the results.

The comparisons in Fig. 4 show that the combined model (Group B) of incorporating the TE function and the time-variable fault detection has better predictive validity. Fig. 6 shows that the relative errors of the combined models (Groups A–D) approach zero faster than for the G-O model and the Yamada S-shaped model: these combined models can provide better estimation for this DS. Table VI shows the relative errors of various DS after the testing phase.

As stated in Section III, FDR is a metric which indicates a trend. It decreases when the software has been used and tested repeatedly, showing reliability growth. It can also increase if the testing techniques/requirements are changed, or new faults are introduced due to new software features or imperfect debugging. The experimental results showed that various SRGM incorporating various TE functions have different trends of FDR, even when they are simulated under the same DS. From the analysis results on 3 actual DS, the larger the FDR is as time progresses (FDR is increasing), the smaller the number of initial faults, and vice versa.
We start our study [9], the first DS might have an imperfect debugging phenomenon, reflecting the characteristic of increasing FDR. In our models, sometimes we use 1 extra parameter to describe the fault detection/removal process, such as \( k_0 \), the slope parameter in (19), or \( \tau_f \), the final FDR in (22). By adding a parameter in modeling the fault-detection process, the estimation procedure is more complicated because more numerical operations are involved. However, this approach does offer a better estimation result as shown in Tables III–V when the combination includes either a reasonable TE function or an adequate FDR function.

REFERENCES


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