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TIME DEPENDENT ERROR DETECTION RATE: SOFTWARE RELIABILITY GROWTH MODELS V/S STATISTICAL TECHNIQUES

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ABSTRACT

There are several software reliability growth models which have been proposed in the past decade. This paper summarizes existing software reliability growth models (SRGM's) described by Non-Homogeneous Poisson Processes. The SRGM's are classified in terms of the software reliability growth index of the error detection rate per error. The comparison made is based on various statistical techniques. The models parameters are estimated by least square estimation (LSE) and maximum likelihood estimation (MLE) methods. The methods of data analysis and comparison criteria are presented. The experimental results from actual data applications show good fit. A comparative analysis to evaluate the effectiveness of the existing models is performed. The maximum-likelihood estimations is used for the SRGM's are discussed for software reliability data analysis and software reliability evaluation by using some statistical tool.

KEYWORDS

Error detection rate per error, maximum likelihood estimation, non homogeneous poission process, software error, software reliability, software reliability growth models.

INTRODUCTION

In recent year's (over the period of last two decade) software system such as operating system, control programs, and application programs have been more complex and larger than ever. It is quite natural to produce reliable software systems efficiently since the breakdown of the computer, which is caused by software errors results in a tremendous loss and damage of social life. Hence software reliability is one of the important key issues in modern era of software product development. In other words software reliability is one of the important issues of today's software development [10]. Several software reliability models have been proposed during past decades. In Software development life cycle, software testing is the phase where a software system is tested to detect software errors remaining in the system and correct them. A Software reliability model describing such an error detection phenomenon is called software reliability growth model, SRGM [10]. An SRGM describe a software error detection process and estimate software remaining in the software. Using software reliability data analysis based on the SRGM, we can evaluate software reliability equation Goel and Okomoto [8], Littlewood [18], Musa [20], Yamda et al.[24]. This paper presents the useful methods of software reliability analysis based on SRGM's described by Non-Homogeneous Poisson Process (NHPP's) and comparison of SRGM's is done with existing statistical techniques which are based on regression analysis. The software reliability growth index of the error detection rate per error which characterizes the software reliability testing phase is defined and the quantitative measures of software reliability evaluation are derived. Rest of the paper is described as follows. Section 2, contains the literature review. In section 3 some of the exiting SRGM's are described with assumptions and notation used to form these models. Section 4 is having information about the statistical tools and curve fitting techniques based on principal of least square. Section 5 is having conclusion obtained on basis of comparison between the two models.

LITERATURE REVIEW

The efforts to improve the software development process are accompanied with parallel efforts aiming at ensuring high quality software systems. The software quality assurance consists of those procedures, techniques and a tool applied by professionals to ensure that a software product meets or exceeds pre-specified standards during software development cycles. The quality of the software system has many attributes such as complexities, maintainability, portability, usability, security, reliability, availability etc.

As the size and complexity of computer systems has grown significantly during the past decades. Computers are used in medical fields, businesses, chemical labs, air traffic control towers, ships, space ships, home appliances, communication, manufacture and many more. Software is a functioning element embedded in computers that plays vital role in the modern life. Errors are bound to happen as software is written by humans. Before, the focus was only on the design and reliability of the hardware. But, now increase in the demand of software has led to the study of the high quality reliable software development. Reliability is the most important aspect since it measures software failures during the process of software development. Software reliability is defined as the probability of failure free operation of a computer program for a specified time in a specified environment (Musa et al., 1987)[20]. Many researches have been conducted over the past decades (Pham, 2000; Lyu, 1996; Musa et al. 1987)[22] and still going on, to study the software reliability. A common approach for measuring software reliability is by using an analytical model whose parameters are generally estimated from available data on software failures (Lyu, 1996[19]; Musa et al. 1987 [22]). A software reliability growth model (SRGM) is a mathematical expression of the software error occurrence and the removal process. In early 1970's, many software reliability growth models (SRGMs) have been proposed (Lyu, 1996[19]; Xie, 1991[27]; Musa et al., 1987 [22]). A Non- homogeneous Poisson process (NHPP) as the stochastic process has been widely used in SRGM. In the past years, several SRGMs based on NHPP which incorporates the fault detection or fault correction process by NHPP following the basic assumption of GO model.(Kapur et.al., 2010)[18] have been proposed by many authors (Yamada et al., 1986; 1987; 1993; Yamada and Ohtera, [25] 1990; Kapur and Garg, 1996[14]; Kapur and Younes, 1994;[17] Huang et al., 1997; 2007;[12,13]; Huang and Kuo, 2002;[11] Huang, 2005;[10] Bokhari and Ahmad, 2006; 2007 [5]; Ahmad et al., 2008; 2009;[6]). The testing-effort can be represented as the number of CPU hours, the number of executed test cases, etc. (Yamada and Osaki, 1984 [23]; Yamada et al., 1986, 1993 [25, 26]). Most of these works on SRGMs modified the exponential NHPP growth model (Goel and Okumoto, 1979) [8] and incorporated the concept of testing-effort into an NHPP model to describe the software fault detection phenomenon.

However, the exponential NHPP growth model is sometimes insufficient and inaccurate to analyze real software failure data for reliability assessment. In this paper we show how to integrate a Log-logistic testing-effort function into inflection S-shaped NHPP growth models (Ohba, 1984; 1984a)[24] to get a better description of the software fault detection phenomenon.

The parameters of the model are estimated by Least Square Estimation (LSE) and Maximum Likelihood Estimation (MLE) methods. The statistical methods of data analysis are presented and the experiments are performed based on real data sets and the results are compared with other existing models.

SOFTWARE RELIABILITY GROWTH MODELS

Let us consider an implemented software system which is tested in the software development. A software failure is defined as an unacceptable departure of program operation caused by a software error remaining in the system.

ASSUMPTIONS

1. A software system is subject to software failures at random times caused by errors present in the system.
2. The initial error content of the software system is a random variable.
3. The number of faults detected at any time instant is proportional to the remaining number of faults in the software.
4. The time between failure (k-1) and k depends on the time to failure (k-1).
5. Each time a failure occurs, the error which caused it, is immediately removed and no other errors are introduced.

NOTATIONS USED

$m(t)$: Expected number of faults identified in (0,*t*], mean value function of NHPP

a, *b* : constants, representing initial fault content and rate of fault removal per remaining for a software.

b (t) : failure detection rate per fault

The testing time such as the calculation time or the machine execution time is generally used as the unit of error detection period which describes the time-dependent behavior of the cumulative number of errors detected by software testing.

Let {N(t), t>=0)} be a counting process representing the cumulative number of errors(or failures) detected in time interval(0,t]. Then the expected value of N(t) called a mean value function of an NHPP ,is defined by M(t). An SGRM based on an NHPP can usually be formulated as

$$\Pr\{N(t)=n\}=\frac{\{M(t)\}^n}{n!}e^{[-M(t)]},t\geq 0 \quad (n=0,1,2,......) \qquad (1)$$

It is consider as

$$M(t)=\int_0^1 m(x)dx \qquad (2)$$

then m(t) is called an intensity function of an NHPP, which means the instantaneous error detection rate. Defining a(= M(∞)) as the expected cumulative number of errors to be eventually detected, i.e., the expected initial error content to be estimated, and can be easily shown as

$$\lim_{t\to\infty} \Pr\{N(t)=n\}=\frac{a^n}{n!}e^{-a} \quad (n=0,1,2,................) \qquad (3)$$

which implies that N(t) obeys a Poisson distribution. with mean a after the testing of infinitely long duration. As a useful software reliability growth index, the error detection rate per error (per unit time) at testing time t is given by

$$d(t)=\frac{m(t)}{[a-M(t)]} \qquad (4)$$

We have the relationship between d(t) and M(t) as

$$M(t)=a[1-e^{(-\int_0^1 d(u)du)}] \qquad (5)$$

The following definitions characterizing a software reliability growth aspect in software testing can be introduced. [11]

Definition 1: M (t) is an increasing error detection rate (IEDR) (mean value) function if d(t) is non-decreasing in t,t≥0.

Definition 2: M (t) is a decreasing error detection rate (DEDR) (mean value) function if d(t) is non-increasing in t, t ≥0.

Definition 3: M (t) is a constant error detection rate (CEDR) (mean value) function if d(t) is constant (t ≥ 0).

Hence a software reliability growth process characterized by the IEDR (DEDR) function indicates increasing (decreasing) test efficiency.

The following random variables are defined for deriving the quantitative measures for software reliability evaluation:

N (t): number of errors remaining in the system at testing time t, i.e., N (∞) - N(t),

Xk: Time interval between (k - 1)st and kth failures(k=(1,2,……….n),

Sk: The kth failure occurrence time, ie, $\sum_{i=1}^{k} Xi$

Then, the expectation and variance of $\overline{N}$ (t) are given by

$$n_r(t)=E[\overline{N}(t)] = ae^{[-\int_0^t d(u)du]} = var[\overline{N}(t)] \qquad (6)$$

The so called software reliability is the conditional survival probability of X_k given that S_{k-1}=t and is given by

$$R(x/t)=\Pr\{X_k > x \mid S_{k-1}=t\} = e^{[a\{e(-\int_0^{t+x} d(u)du)} - e^{(-\int_0^t d(u)du)\}]} \qquad (7)$$

which is independent of k. The software reliability presents the probability that a failure does not occur in (t, t+x].

EXISTING SRGM'S

A software reliability growth curve representing a relation between the time span of software testing and the cumulative number of detected errors is observed in a software testing phase.

There are two types of shape for the observed software reliability growth curve: exponential and s-shaped software reliability growth curves are called the exponential and s-shaped SRGM's respectively. There are several software reliability growth models based on NHPP are briefly summarized below.

Goel and Okomoto [8] first proposed an SRGM based on NHPP. This model is called exponential SRGM, which describes a software failure detection phenomenon. The mean value function showing an exponential growth curve as

$$m(t) = a(1-e^{-bt}), \quad b>0 \qquad (8)$$

where b is the error detection rate per error t an arbitrary testing time.

Delayed S-shaped SRGM [8] fault detection in this model is assumed to be a two-phase process consisting of failure detection and it's eventual removal by isolation. It takes into account the time taken to isolate and remove a fault and so it is important that the data to be used here should be that of fault isolation. It is further assumed that the number of faults isolated at any time instant is proportional to the number of faults remaining in the software. Failure rate and isolation rate per fault are assumed to be same and equal to b.

Thus

$$\frac{d}{dt} m_f(t) = b[a - m_f(t)] \quad \ldots \qquad (9)$$

$$\frac{d}{dt} m(t) = b[m_f(t) - m(t)] \quad \ldots \qquad (10)$$

$m_f(t)$ is the expected number of failures in $(0,t]$. Solving (9) and (10), which gives the mean value function as

$$m(t) = a\{1 - (1 + bt)e^{-bt}\} \quad \ldots \qquad (11)$$

Alternately the model can also be formulated as one stage process directly as follows.

$$\frac{d}{dt} m(t) = \left(\frac{b^2 t}{1+bt}\right)(a - m(t)) \quad \ldots \qquad (12)$$

It is observed that $\frac{b^2 t}{1+bt} \to b$ as $b \to \infty$. This model was specifically developed to account for lag in the failure observation and its subsequent removal. This kind of derivation is peculiar to software reliability only.

Another S-Shaped SRGM was proposed by Ohba[11] The model is called Inflection S-Shaped SRGM, which describes a software failure detection phenomenon with a mutual dependence of detected errors. In the error detection process, the more failures we detect, the more undetected failures become detectable. This NHPP model has mean value function of

$$M(t)=I(t)= \frac{a[1 - e^{-bt}]}{[1 + c.e^{-bt}]}, \quad b>0,\ c>0, \qquad (13)$$

which shows an S-Shaped growth curve. The parameters b and c represent the failure detection rate and the inflection factor, respectively.

Here three models having M(t) ,mean value function with NHPP are compared for actual data. The models compared are : the NHPP model and two deterministic models of fitting curves ie logistic and Gompertz Curves, based on regression analysis . They are denoted as GO(Goel and Okomoto), LC (Logistic curve) and GC (Gompertz Curve) respectively .

The table below shows the result of cumulative number of detected error during the test and after the test . ie. Na and Ne is the estimated s-expected number of errors to be eventually detected based on each models .

Ie

$$A = \left|\frac{N_a - N_e}{N_a}\right|$$

The result where N_a =42 in the criterion of the accuracy of estimation ie 11 additional errors where detected during the subsequent on-line system test and the actual operational of the program.

TABLE 1: ESTIMATION USING SRGM'S MODEL

Models	Criterion for Comparison		
	F	A	Est. Error
NHPP Model With M(t)	12.6	9.7%	37.9
GO Model	31.5	160.6%	109.5
LC Model	767	37.0%	26.5
GC Model	794	18.6%	34.2

Where "F" is the sum of square of the differences and is given by

$$F = \sum_{i=1}^{10} (N_k - \hat{N}_k)^2$$

N_k = Actual Cumulative number of errors

$\hat{N}_k$ = Estimated number of errors detected upto time t_k (k=1,2.3..........10)

and

A is the accuracy of estimation

STATISTICAL TECHNIQUE: CURVE FITTING

In this method the square of the difference between observed response and value predicted by the model is minimized. If the expected value of the response variable is given by $\hat{m}(t)$ (can be a mean value function of an SRGM), then the least square estimators of the parameters of the model may be obtained from *n* pairs of sample values (t_1, y_1), (t_2, y_2), …, (t_n, y_n) by minimizing *J* given by

$$J = \sum_{i=1}^{n} \left[y_i - \hat{m}(t) \right]^2 \qquad \ldots \qquad (14)$$

t_i and y_i observed values of explanatory and dependent variables respectively. For small and medium size samples least square estimation is preferred.

Linear – In this case the expected faults is considered to be linearly distributed as

y = ax + b, where x represent time axis and y represent the number of faults.

Quadratic- This is the enhance version of liner method described above in which faults are assumed to be quadratic in nature given by, y= ax^2+bx+c. It has been seen that as the degree of equation increases the prediction error decreases.

Exponential – This is the alternate way when the degree of fitting the curve is not predictable. Exponential smoothing itself take care of fitting of curve besides the presence of number of curve in original data.

Model Description

Model Name		MOD_2
Dependent Variable	1	days of failure
Equation	1	Linear
	2	Quadratic
	3	Exponential[a]
Independent Variable		failure interval length
Constant		Included
Variable Whose Values Label Observations in Plots		faliure no.
Tolerance for Entering Terms in Equations		.0001

a. The model requires all non-missing values to be positive.

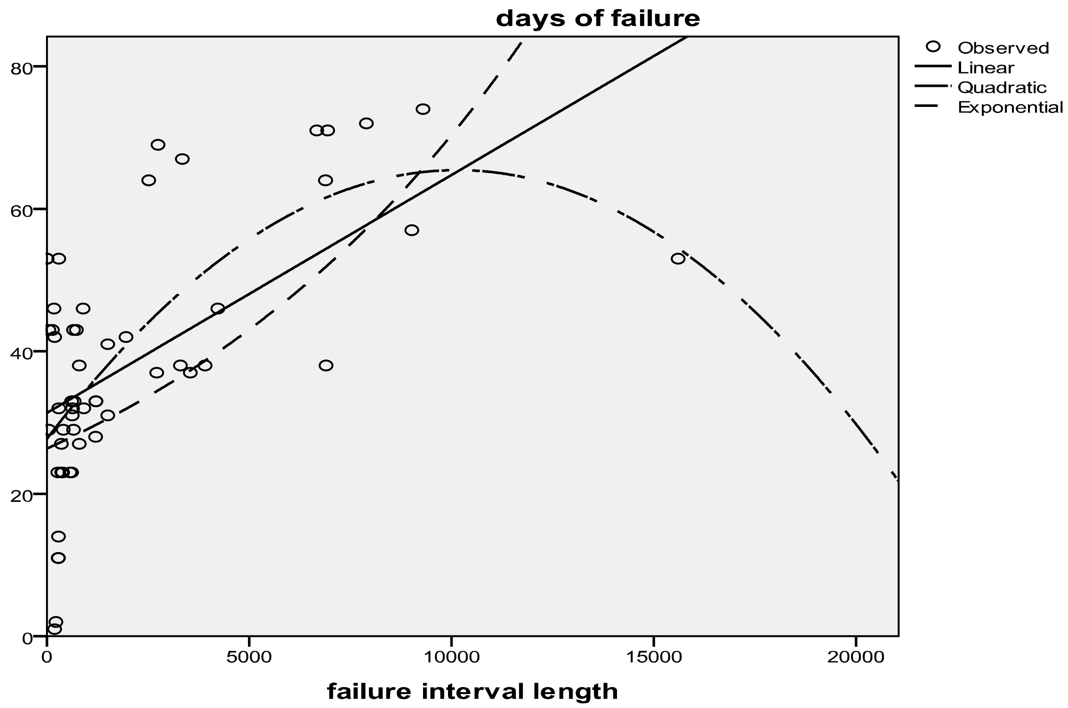
TABLE 2: ESTIMATION USING STATISTICAL MODEL

Model Summary and Parameter Estimates

Dependent Variable:days of failure

Equation	Model Summary					Parameter Estimates		
	R Square	F	Df1	df2	Sig.	Constant	b1	b2
Linear	.355	29.115	1	53	.000	31.343	.003	
Quadratic	.450	21.275	2	52	.000	27.685	.007	-3.670E-7
Exponential	.163	10.357	1	53	.002	26.336	9.826E-5	

The independent variable is failure interval length.



MAXIMUM LIKELIHOOD ESTIMATION

Maximum Likelihood Estimation (MLE) method has been extensively adopted for estimation of parameters of SRGMs based upon NHPP [7]. We briefly discuss below the MLE procedure for two types of software failure data discussed above.

For the first type of data, suppose that estimation is to be performed at a specified time t_k, not necessarily corresponding to a failure, and with total of m_k failures being experienced at time $t_1, t_2, \ldots, t_{m_k}$. Then the likelihood function for the NHPP [7] discussed above is:

$$L = \left[\prod_{i=1}^{k} \lambda(t_i) \right] e^{-\int_0^{t_k} \lambda(x) dx} \quad \ldots \quad (15)$$

The MLE of the Parameters can be obtained by maximizing Likelihood function or its Log likelihood function (log *L*).

If the software failure data is grouped into *k* points (t_i, y_i); *i* = 1,2,...,*k*, where y_i is the cumulative number of failure reports at time t_i. Then the Likelihood function L is given as follows:

$$L \equiv \prod_{i=1}^{k} \frac{[m(t_i) - m(t_{i-1})]^{y_i - y_{i-1}}}{(y_i - y_{i-1})!} e^{-\{m(t_i) - m(t_{i-1})\}} \quad \ldots \quad (16)$$

Taking natural logarithm of (5.2.3) we get the log likelihood function

$$LogL = \sum_{i=1}^{k} (y_i - y_{i-1}) \ln[m(t_i) - m(t_{i-1})] - m(t_k) - \sum_{i=1}^{k} \ln[(y_i - y_{i-1})!] \quad \ldots \quad (17)$$

The MLE of the parameters of SRGM can be obtained by maximizing (eq. 17) with respect to the model parameters.

Likelihood functions for NHPP models are defined above as most of the stochastic models discussed in this thesis are based upon NHPP assumptions. Both the estimation procedures can also be applied to other stochastic processes. Maximum likelihood estimators possess many desirable properties such as consistency, efficiency, asymptotic normality and the invariance property. Hence it is the most preferred estimation procedure for relatively large sample size.

CONLCUSION

On the basis of table 1 and table 2 it can be concluded that sometime the regression analysis techniques are better than the SRGM's models. The experimental results show that the proposed SRGM with Log-logistic testing-effort function can estimate the number of initial faults better than that of other models and that the Log-logistic testing-effort functions is suitable for incorporating into inflection S-shaped NHPP growth model.

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