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Generalization of the Testing-Domain Dependent NHPP SRGM and Its Application

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Abstract. This paper proposes a new non-homogeneous Poisson process software reliability growth model based on the coverage information. The new model incorporates the coverage information in the fault detection process by assuming that only the faults in the covered constructs are detectable. Since the coverage growth behavior depends on the testing strategy, the fault detection process is first modeled for the general testing strategy and then realized for the uniform testing. Finally the model for the uniform testing is empirically evaluated by applying it to real data sets.

Key Words : *coverage, fault detection rate function, software reliability growth model, testing-domain function, uniform testing.*

1. INTRODUCTION

Recently software is becoming an integral part of computer systems. Since failures of a software system can cause severe consequences, reliability of a software system is a primary concern for both software developers and software users. Testing is a key activity for detecting and removing faults and improving reliability of

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a software system. In theory, it is impossible to detect and remove all the faults within a reasonable amount of testing time. Therefore developers usually determine when to stop testing and release the software based on the estimates of reliability measures such as the initial fault content, the time to next failure, and the number of remaining faults. Many software reliability growth models (SRGM's) have been proposed and applied in practice to estimate such software reliability measures.

One of the most popular SRGM's is the class of nonhomogeneous Poisson process (NHPP) SRGM's. An NHPP SRGM expresses the fault detection/removal process during testing as a stochastic process. Let $N(t)$ denote the number of faults detected up to t testing time. Assuming that the detected faults are removed immediately, $N(t)$ represents the fault detection/removal process. An NHPP SRGM assumes that $N(t)$ follows a Poisson distribution with mean value function (MVF) $m(t)$. An NHPP SRGM is thus characterized by its MVF. MVF's of the existing NHPP SRGM's are usually derived from the assumption that failure intensity is proportional to the number of faults remaining in the software under testing. Thus Yamada and Osaki (1985) presented a framework for the NHPP SRGM's as the following differential equation:

$$\frac{dm(t)}{dt} = b(t)\left[a - m(t)\right] , \tag{1.1}$$

where a is the initial fault content and $b(t)$ is the fault detection rate function. The fault detection rate function expresses the fault detection rate per fault at testing time t. Recently the NHPP SRGM's have been generalized so that the imperfect debugging is incorporated in the model. Pham and Nordmann (1997) refers to such NHPP SRGM's as the general NHPP SRGM's. The framework for the general NHPP SRGM's is represented as

$$\frac{dm(t)}{dt} = b(t)\left[a(t) - m(t)\right] , \tag{1.2}$$

where $a(t)$ is the fault content function. Various $a(t)$'s and $b(t)$'s reflect various assumptions on the software testing process. A constant $a(t)$ implies the perfect debugging; an increasing $a(t)$ reflects the imperfect debugging. A constant $b(t)$ means that the failure intensity is proportional to the number of faults remaining in the software system; an increasing $b(t)$ implies that the fault detection rate per fault varies due to, for example, the learning phenomenon during testing. Several combinations of $a(t)$ and $b(t)$ have been proposed and the corresponding general NHPP SRGM's have been compared with the existing NHPP SRGM's by Pham and Nordmann (1997), Pham and Zhang (1997), Pham et al (1999) and Pham (2003).

There is another approach to the development of NHPP SRGM's. The approach takes advantage of coverage information. Denote by M the set of all the constructs of the software under testing. Constructs may be statements, blocks, p-uses, or c-uses depending on the coverage metric under consideration. Let $|M|$ be the cardinality of set M. As the testing progresses, the cumulative numbers of executed test cases and covered constructs increase. We represent the set of constructs covered up to testing time t by $M_c(t)$. Then the coverage at testing time t is defined as $c(t) = |M_c(t)||M|^{-1}$ and referred to as the coverage growth function. Only a few coverage-based SRGM's have appeared in Piwowarski et al (1993), Gokhale et al (1996) and Malaiya et al (2002). Piwowarski, et al (1993) proposed the first coverage-based SRGM, which has the MVF $m(t) = ac(t)$, where $c(t) = 1 - \exp\left(1 - p|M|^{-1}t\right)$ and p is the expected number of constructs executed by a test case. Gokhale et al (1996) suggested an enhanced NHPP SRGM, which is represented by

$$\frac{dm(t)}{dt} = ab(t)\frac{dc(t)}{dt}\,. \tag{1.3}$$

Appropriate $b(t)$ and $c(t)$ are to be specified for application of the enhanced NHPP SRGM. The logarithmic-exponential coverage model of Malaiya et al (2002) was derived under the assumption that both $c(t)$ and $m(t)$ follow the logarithmic Poisson execution time model.

All the faults detected up to testing time t are from $M_c(t)$, not from $\overline{M_c(t)} = M - M_c(t)$. It should be noted that coverage of a construct does not always reveal all the faults in that construct. This implies that constructs in $\overline{M_c(t)}$ may possess faults. An additional test case generated at testing time t according to a testing strategy generally executes some constructs in $M_c(t)$ and some constructs in $\overline{M_c(t)}$. That is, repeated construct execution occurs during testing. Therefore faults newly detected by the additional test cases may be located at either $M_c(t)$ or $\overline{M_c(t)}$. The coverage-based NHPP SRGM's mentioned above do not explicitely take location of the newly detected faults into account. The testing-domain (T-D) dependent NHPP SRGM of Yamada and Fujiwara (2001) and Fujiwara and Yamada (2002), represented by

$$\frac{dm(t)}{dt} = b(t)\left[u(t) - m(t)\right]\,, \tag{1.4}$$

is the only NHPP SRGM taking account of the location of newly detected faults. Here, the T-D function $u(t)$ denotes the number of all the faults (detected and undetected) in $M_c(t)$. The key concept in the T-D dependent NHPP SRGM is the T-D function, which reflects the fact that only the faults in $M_c(t)$ are detectable. Yamada and Fujiwara (2001) and Fujiwara and Yamada (2002) model the time-dependent growth behavior of $u(t)$ under the assumption that the growth rate of $u(t)$ is proportional to the number of faults remaining in $\overline{M_c(t)}$. However, this assumption does not represent the real testing environment well enough. The growth behavior of $u(t)$ depends on the growth behavior of $M_c(t)$. The growth behavior of $M_c(t)$ in turn depends on the testing strategy. That is, without explicitely considering the testing strategy, the growth behavior of $u(t)$ can not be adequately described.

The primary objective of this paper is to develop the general T-D dependent NHPP SRGM that explicitely reflects the testing strategy. First the fault detection process in a general testing environment is modeled as a differential equation for MVF in Section 2. Then the general T-D dependent NHPP SRGM for the uniform testing profile is obtained in Section 3 by realizing the differential equation for the uniform testing profile. For practical application of the general T-D dependent NHPP SRGM, the fault detection rate function should be provided. Section 4 derives MVF's of the general T-D dependent NHPP SRGM for several well-known fault detection rate funations. Section 5 performs empirical evaluation of the proposed model by applying it to two real data sets. Finally conclusions are presented in Section 6.

2. MODELING FAULT DETECTION PROCESS FOR GENERAL TESTING STRATEGY

As mentioned in Section 1, coverage of a construct does not guarantee that the construct is fault free. Thus $M_c(t)$ may contain some faults. Such imperfect fault detection phenomenon is reflected in the fault detection rate function $b(t)$. The faults in $M_c(t)$ can be detected later when some constructs in $M_c(t)$ are executed again. Suppose that additional testing is performed at testing time t during dt. In general, the additional testing will execute some constructs in $\overline{M_c(t)}$ and some constructs in $M_c(t)$. Execution of constructs in $\overline{M_c(t)}$ expands $M_c(t)$ and consequently increases both $c(t)$ and $u(t)$. The constructs which were in $\overline{M_c(t)}$ at time t and covered during dt constitutes the increment of $M_c(t)$, which is denoted by $dM_c(t)$. The set of constructs which were in $M_c(t)$ at time t and re-executed during dt is denoted by $RM_c(t)$. Similarly we denote the corresponding increments of $m(t)$, $u(t)$ and $c(t)$ caused by the additional testing during dt by respectively $dm(t)$, $du(t)$ and $dc(t)$. It is easily verified that $u(t) = n_T(M_c(t))$, $du(t) = n_T(dM_c(t))$, and $dc(t) = |dM_c(t)||M|^{-1}$, where $n_T(\cdot)$ denote the total number of (detected and undetected) faults in a set of constructs. The increment $dm(t)$ is the sum of the number of faults detected in $dM_c(t)$ and the number of faults detected in $RM_c(t)$. Therefore,

$$\begin{aligned} dm(t) &= b(t)\, n_R(RM_c(t)) + b(t)\, n_T(dM_c(t)) \\ &= b(t)\, n_R(RM_c(t)) + b(t)\, du(t)\,, \end{aligned} \tag{2.1}$$

where $n_R(\cdot)$ is the number of (undetected) faults remaining in a set of constructs.

Henceforth we model the fault detection process based on the following assumptions:

1. The a initial faults are uniformly distributed over M.
2. The faults remaining in $M_c(t)$ are uniformly distributed over $M_c(t)$.
3. The detected faults are immediately removed without introduction of new faults.

The total number of (detected and undetected) faults in the software, a, remains constant throughout testing due to Assumption 3. Assumption 1 implies that $u(t)$ is obtained as the product of the initial fault density per construct in $M_c(t)$ and $|\overline{M_c(t)}|$ and that $du(t)$ is obtained as the product of the fault density per construct in $\overline{M_c(t)}$ and $|dM_c(t)|$. Since both the fault density per construct in M at the beginning of testing and the fault density per construct in $\overline{M_c(t)}$ are $a|M|^{-1}$,

$$u(t) = a|M|^{-1}|M_c(t)| = a\,c(t) \tag{2.2}$$

and

$$du(t) = a|M|^{-1}|dM_c(t)| = a\,dc(t)\,. \tag{2.3}$$

It is worthy of note that the T-D function $u(t)$ is completely determined by the coverge growth function $c(t)$ under Assumptions 1 and 3. Similarly, due to Assumption 2, $n_R\,(RM_c(t))$ is obtained as the product of the fault density per construct in $RM_c(t)$ and $|RM_c(t)|$. Since the fault density per construct in $RM_c(t)$ is just the fault density per construct in $M_c(t)$ and $n_R\,(M_c(t)) = [u(t) - m(t)]$,

$$n_R\,(RM_c(t)) = \frac{u(t) - m(t)}{|M_c(t)|}|RM_c(t)| = \frac{ac(t) - m(t)}{|M|c(t)}|RM_c(t)|\,. \tag{2.4}$$

Substituting Eqs. (??) and (??) into Eq. (??) and dividing both sides of Eq. (??) by dt, we have the following differential equation:

$$\frac{dm(t)}{dt} = b(t)\frac{ac(t) - m(t)}{|M|c(t)}\frac{|RM_c(t)|}{dt} + b(t)a\frac{dc(t)}{dt}\,. \tag{2.5}$$

Hereafter, the NHPP SRGM whose MVF is represented by Eq. (??) is referred to as the general T-D dependent NHPP SRGM. Apparently the general T-D dependent NHPP SRGM is characterized by the time-dependent behavior of $RM_c(t)$ and $c(t)$. Their behavior is determined by the testing strategy. The next section realizes the general T-D dependent NHPP SRGM for the testing strategy employing the uniform testing profile.

3. GENERAL T-D DEPENDENT NHPP SRGM FOR UNIFORM TESTING

The general T-D dependent NHPP SRGM derived in the previous section is not yet applicable in practice. Because Eq. (??) can not be solved without specifying the testing strategy. For example, consider the resource-constrained non-operational testing of Rivers and Vouk (1998), which does not allow the repeated execution of constructs in $M_c(t)$. Then $|RM_c(t)| = 0$ and Eq. (??) is simplified to Eq. (??). This implies that the enhanced NHPP SRGM is equivalent to the general T-D dependent NHPP SRGM for the testing strategy without repeated construct execution.

In the remainder of this section we realize the general T-D dependent NHPP SRGM for the uniform testing. Consider the following assumption:

4. All constructs in M are equally likely executable.

This assumption is referred to as the uniform testing profile assumption. The unform testing is a testing strategy in which test cases are generated according to the uniform testing profile. One of important reliability measures is the number of faults remaining in the software. When the primary objective of testing is to improve reliability by removing as many faults as possible and/or the managemental decision on when to stop testing is made based on the number of remaining faults, all the faults in the software should be considered equally important. Then it is reasonable to employ a testing profile distributing equal frequencies over all the constructs. Even when the operational profile is not available, the uniform testing profile may be used as a reasonable alternative.

Suppose additional testing is performed at t during dt according to the uniform testing profile. Then $|RM_c(t)|/|dM_c(t)|$ is expected to be $c(t)\,[1-c(t)]^{-1}$. Since $|dM_c(t)| = |M|dc(t)$, $|RM_c(t)|$ is thus expected to be $|M|c(t)\,[1-c(t)]^{-1}\,dc(t)$. Replacing $|RM_c(t)|$ in Eq. (??) with $|M|c(t)\,[1-c(t)]^{-1}\,dc(t)$, Eq. (??) is now written as

$$\frac{dm(t)}{dt} = b(t)\frac{a-m(t)}{1-c(t)}\frac{dc(t)}{dt}\,. \tag{3.1}$$

Next we derive the coverage growth function $c(t)$ for the uniform testing strategy. Let p denote the expected number of constructs executed during a unit testing time. Then the number of constructs newly covered during dt, $|dM_c(t)|$, is expected to be $p\,[1-c(t)]\,dt$. Since $dc(t) = |dM_c(t)||M|^{-1}$, the coverage growth behavior is represented by

$$\frac{dc(t)}{dt} = \frac{p}{|M|}\,[1-c(t)]\,. \tag{3.2}$$

Soving this differential equation with initial condition $c(t) = 0$, the coverage growth function is obtained as

$$c(t) = 1 - \exp\left(-\frac{p}{|M|}t\right)\,. \tag{3.3}$$

Actually this coverage growth function is identical with the coverage growth function of Piwowarcki, et al (1993). Substituting Eq. (??) into Eq. (??), we now have

$$\frac{dm(t)}{dt} = \frac{p}{|M|}b(t)\,[a-m(t)]\,. \tag{3.4}$$

Eqs. (??) and (??) assume that all the faults remaining in the software are detectable during dt. Since $p^{*} = p|M|^{-1}$ is the average proportion of constructs covered during a unit testing time, $p^* [a - m(t)]$ denotes the average number of faults in the constructs covered during a unit testing time. Therefore, Eq. (??) implies that only the faults remaining in the constructs covered during dt are exposed to the detection activity. Evidently Eq. (??) represents the fault detection process more reasonably than Eqs. (??) and (??). The MVF of the general T-D dependent NHPP SRGM for the uniform testing strategy is then obtained as

$$m(t) = a \left[1 - \exp\left(-p^* \int_0^t b(\tau) d\tau \right) \right] . \tag{3.5}$$

4. FAULT DETECTION RATE FUNCTIONS AND CORRESPONDING MVF's

The MVF of the general T-D dependent NHPP SRGM for the uniform testing is not yet determined. The MVF is completely determined when the fault detection rate function is specified. Since the fault detection rate function reflects the learning phenomenon occurring during testing, the traditional learning curves may be employed as the fault detection rate function. Alternatively we can choose an appropriate fault detection rate function from the available fault detection rate functions appeared in the literature, e.g., Goel and Okumoto (1979), Yamada et al (1986), Yamada et al (1992), Yamada et al (1993), Pham and Nordmann (1997), Pham and Zhang (1997), Pham et al (1999), and Pham (2003). The currently available fault detection rate functions and corresponding MVF's for the general T-D dependent NHPP SRGM are tabulated in Table 1. Comparison of Eq. (??) and Eq. (??) indicates that the general T-D dependent NHPP SRGM for the uniform testing can be regarded as the NHPP SRGM with fault detection rate function $p^*b(t)$. Furthermore, if $p^*b(t)$ has the same functional form with $b(t)$, the general T-D dependent NHPP SRGM for the uniform testing is equivalent to the NHPP SRGM. The fault detection rate functions in Table 4.1 are thus classified into two categories: scale-variant fault detection rate function and scale-invariant fault detection rate function. If $p^*b(t)$ has the same functional form with $b(t)$, $b(t)$ is said to be scale-invariant. Otherwise, $b(t)$ is said to be scale-variant. That is, if scalar multiplication does not alter the functional form of $b(t)$, $b(t)$ is scale-invariant. If $b(t)$ is scale-invariant, we can simply regard $p^*b(t)$ as $b(t)$ without loss of generality. Consequently the MVF of the general T-D dependent NHPP SRGM with scale-invariant $b(t)$ for the uniform testing is equal to that of the NHPP SRGM with the same fault detection rate function. It is not difficult to verify that the MVF's corresponding to the first 4 scale-invariant fault detection rate functions in Table 4.1, denoted by $m_i(t)$ for $i = 1, 2, 3, 4$, are identical with the MVF's of the well-known NHPP SRGM's proposed in Goel and Okumoto (1979), Yamada et al (1986) and Yamada et al (1993).

Next we consider the last 3 fault detection rate functions in Table 4.1. Suppose that the fault rate function is given by

$$b(t) = \frac{\gamma}{1 + \alpha \exp(-\beta t)} . \quad (4.1)$$

Since this fault detection rate function is scale-invariant, p^* can be simply ignored according to the discussion of the previous paragraph. The corresponding MVF of the general T-D dependent NHPP SRGM for the uniform testing is thus obtained as

$$m_5(t) = \left[1 - \left[\frac{(1+\alpha)\exp(-\beta t)}{1 + \alpha \exp(-\beta t)}\right]^{\gamma/\beta}\right] . \quad (4.2)$$

Now consider the case where the fault detection rate function is

$$b(t) = \frac{\beta}{1 + \alpha \exp(-\beta t)} . \quad (4.3)$$

When multiplied by p^*, $p^*b(t)$ is transformed into Eq. (??) by letting $\gamma = p^*\beta$. Therefore, the MVF for the fault detection rate function (??) is also given by Eq. (??). If the fault detection rate function is

$$b(t) = \frac{\beta^2 t}{1 + \beta t} , \quad (4.4)$$

$p^*b(t)$ can be written as

$$p^*b(t) = \frac{\gamma t}{1 + \beta t} \quad (4.5)$$

where $\gamma = p^*\beta^2$. The corresponding MVF is then obtained as

$$m_6(t) = a\left[1 - (1 + \beta t)^{\gamma/\beta^2} \exp(-\gamma t/\beta)\right] . \quad (4.6)$$

Table 4.1. Fault detection rate functions and corresponding MVF's.

Category	Fault Detection Rate Function	MVF
	$b(t) = \beta$	$m_1(t) = a[1 - \exp(-\beta t)]$
Scale-	$b(t) = \alpha\beta \exp(-\beta t)$	$m_2(t) = a[1 - \exp[-\alpha[1 - \exp(-\beta t)]]]$
invariant	$b(t) = \alpha\beta t \exp(-\beta t^2/2)$	$m_3(t) = a[1 - \exp[-\alpha[1 - \exp(-\beta t^2)]]]$
	$b(t) = \alpha\beta\gamma t^{\gamma-1} \exp(-\beta t^{\gamma})$	$m_4(t) = a[1 - \exp[-\alpha[1 - \exp(-\beta t^{\gamma})]]]$
	$b(t) = \frac{\gamma}{1+\alpha \exp(-\beta t)}$	$m_5(t) = a\left[1 - \left[\frac{(1+\alpha)\exp(-\beta t)}{1+\alpha \exp(-\beta t)}\right]^{\gamma/\beta}\right]$
Scale-	$b(t) = \frac{\beta^2 t}{1+\beta t}$	$m_6(t) = a\left[1 - (1+\beta t)^{\gamma/\beta^2} \exp(-\gamma t/\beta)\right]$
variant	$b(t) = \frac{\beta}{1+\alpha \exp(-\beta t)}$	$m_5(t) = a\left[1 - \left[\frac{(1+\alpha)\exp(-\beta t)}{1+\alpha \exp(-\beta t)}\right]^{\gamma/\beta}\right]$

5. APPLICATION TO REAL DATA SETS

In this section we evaluate the practical applicability of the general T-D dependent NHPP SRGM for the uniform testing. Two data sets are considered for the practical applicability evaluation. The first data set DS1, reported in Tohma et al (1991), is the number of failures recorded by day from testing a real-time monitor and control system. A number of currently available NHPP SRGM's are applied to DS1 and compared in terms of two performance measures, SSE (sum of squared errors) and AIC (Akaike information criterion). The lower are the SSE and AIC values, the better the model performs. Zhang and Pham (2000) chooses the P-Z model as the best model among the NHPP models applied to DS1. The general T-D dependent NHPP SRGM's whose MVF's are $m_i(t)$ for $i = 4, 5, 6$ and the T-D dependent NHPP SRGM with skill-factor of Yamada and Fujiwara (2001) are now applied to DS1. The values of SSE and AIC for the models are computed and presented in Table 5.1. The T-D dependent NHPP SRGM with skill-factor is the best for DS1 with respect to AIC, while the general T-D dependent NHPP SRGM with MVF $m_5(t)$ is the best with respect to SSE. We may choose the general T-D dependent NHPP SRGM with MVF $m_4(t)$ because its SSE and AIC values are close to the corresponding best values. The maximum likelihood estimates of the parameters in the general T-D dependent NHPP SRGM with MVF $m_5(t)$ are computed and presented in Table 5.2. The estimated MVF is depicted in Figure 5.1.

Table 5.1. Values of SSE and AIC of some selected models for DS1.

	general T-D dependent NHPP with MVF			T-D dependent NHPP with skill-factor	P-Z model
	$m_4(t)$	$m_5(t)$	$m_6(t)$		
SSE	33062.2900	31546.4747	37424.8166	38012.4546	59549
AIC	640.4559	643.5667	646.0102	638.4159	890.62

The second data set DS2, reported in Fujiwara and Yamada (2002), was observed in the testing phase of a software of which size is 197.2x10^3. DS2 consists of by the number of faults detected weekly. It was shown that the T-D dependent NHPP SRGM with skill-factor worked better than other conventional models for DS2. The general T-D dependent NHPP SRGM with MVF $m_5(t)$ is now applied to DS2. The values of SSE and AIC for the general T-D dependent NHPP SRGM with MVF $m_5(t)$ and the T-D dependent NHPP SRGM with skill-factor are given in Table 5.3 for the sake of comparison. The maximum likelihood estimates of the parameters in the general T-D dependent NHPP SRGM with MVF $m_5(t)$ are also presented in

Table 5.2. Maximum likelihood estimates of the parameters in the general T-D dependent NHPP SRGM with MVF $m_5(t)$ for DS1 and DS2.

	Data Set	
parameter	DS1	DS2
a	481.7499	298.2275
α	4.3958	12.8596
β	0.0634	0.2807
γ	0.0766	0.3334

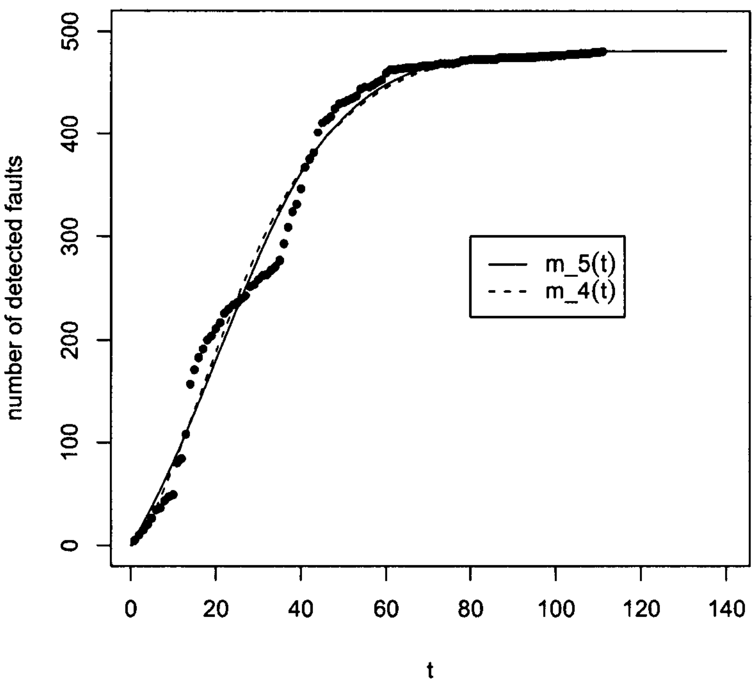

Figure 5.1. Plots of the cumulative number of detected faults and the estimated $m_5(t)$. (DS1)

Table 5.2. The fitted MVF is plotted in Figure 5.2. Judging from Table 5.3 and Figure 5.2, it is evident that the general T-D dependent NHPP SRGM with MVF $m_5(t)$ fits to DS2 significantly better than the T-D dependent NHPP SRGM with skill-factor.

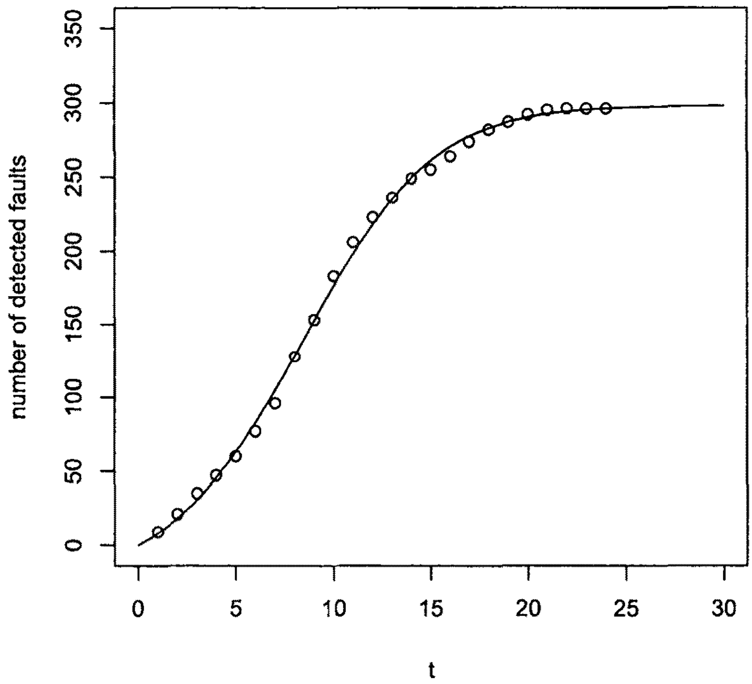

Figure 5.2. Plots of the cumulative number of detected faults and the estimated $m_5(t)$. (DS2)

6. CONCLUSIONS

The T-D dependent NHPP SRGM assumes that only the faults in the covered constructs are detectable. Since the coverage growth depends on the testing strategy, the T-D dependent NHPP SRGM is generalized so that the coverage growth in the general testing strategy is incorporated. We first model the fault detection process under the general testing strategy in which the repeated execution of constructs is allowed. We then realize the model for the uniform testing. Finally it is shown

Table 5.3. Values of SSE and AIC of some selected models for DS2.

	general T-D dependent NHPP with MVF $m_5(t)$	T-D dependent NHPP with skill-factor
SSE	402.9407	1645.2275
AIC	121.9217	133.508

empirically that the general T-D dependent NHPP SRGM works well in comparison with the existing models.

There are several points that need further research. The general T-D dependent NHPP SRGM proposed in this paper is developed under the perfect debugging assumption. To make the proposed model realistic, we need to modify it to reflect the imperfect debugging phenomenon. The general T-D dependent NHPP SRGM has been realized only for the uniform testing. The uniform testing is just an approximation to the actual testing. The actual testing may be far different from the uniform testing. Thus the effect of the discrepancy between the uniform testing and the actual testing need to be evaluated. In addition, the general T-D dependent NHPP SRGM is to be realized for testing strategies other than the uniform testing.

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