PAPER *Special Section on Dependable Computing*

Optimal Trigger Time of Software Rejuvenation under Probabilistic Opportunities

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SUMMARY This paper presents the opportunity-based software rejuvenation policy and the optimization problem of software rejuvenation trigger time maximizing the system performance index. Our model is based on a basic semi-Markov software rejuvenation model by Dohi et al. 2000 under the environment where possible time, called opportunity, to execute software rejuvenation is limited. In the paper, we consider two stochastic point processes; renewal process and Markovian arrival process to represent the opportunity process. In particular, we derive the existence condition of the optimal trigger time under the two point processes analytically. In numerical examples, we illustrate the optimal design of the rejuvenation trigger schedule based on empirical data.
key words: *software aging, software rejuvenation, time-triggered policy, opportunity-based policy, renewal process, Markovian arrival process, optimization*

1. Introduction

In highly dependable systems, preventive maintenance is one of the most important key strategies to enhance system reliability and availability in their operation phase. During last several decades, the preventive maintenance was widely researched for both hardware and software systems. Especially, in recent years, the preventive maintenance for software system called *software rejuvenation* draws attention as a low-cost fault-tolerant technique along with the concept of *software aging*.

Software aging has already known as a cumbersome problem in the operation of computer-aided system. The software aging is caused by aging-related bugs [1] such as memory leak, fragmentation and accumulating round-off errors. The aging-related bugs gradually degrade the system performance due to exhaustion of system resources and eventually cause the system failure. Empirically, it is difficult to detect and remove aging-related bugs in testing phase. In general, the software aging can be predicted by monitoring system attributes such as operation time and workload. That is, we can execute a proactive action to prevent the system failure caused by the software aging. Such proactive actions are called software rejuvenation. Typical examples of the software rejuvenation are garbage collection, flushing operating system kernel tables, reinitializing internal data structures and hardware reboot [2], [3].

The software rejuvenation is a significant technique for the system to run continuously for long periods of time. One of the main issues of the software rejuvenation is when to start the rejuvenation operation, because time overheads are incurred by the rejuvenation operation. Two approaches were discussed to determine when to start the software rejuvenation: model-based and measurement-based approaches. In the model-based approach, we build a state-based model such as a continuous-time Markov chain (CTMC) representing behavior of software aging and rejuvenation in order to determine the optimal rejuvenation timing under a given rejuvenation policy. On the other hand, the measurement-based approach is to monitor system attributes to find a significant sign of the software aging, and is to determine the condition to trigger the software rejuvenation.

Rejuvenation policies are generally categorized to time-triggered and condition-triggered policies. Under the time-triggered policy, the system performs the rejuvenation operation according to a certain time schedule. The advantage of time-triggered policy is a simple implementation of the rejuvenation. In fact, the time-triggered policy was adopted in many model-based approaches. For instance, Garg et al. [4] introduced a periodic time-triggered policy and represented the behavior of system by using a Markov regenerative stochastic Petri net (MRSPN). Also, Dohi et al. [5] and Suzuki et al. [6] developed semi-Markov models and statistically non-parametric algorithms to determine the optimal rejuvenation policy under the periodic time-triggered rejuvenation. On the other hand, the condition-triggered policy utilizes system attributes other than the operation time to determine a rejuvenation schedule. The measurement-based approach mainly adopts the condition-triggered policy. Vaidyanathan et al. [7] treated the measurement-based approach to estimate time to exhaustion of operating system resources. Alonso et al. [8] developed an on-line algorithm for the prediction of resource exhaustion.

This paper focuses on an intermediate policy between time-triggered and condition-triggered policies. The disadvantage of time-triggered policies is not to take account of the operational condition of software system, namely, the system is forced to perform the software rejuvenation at a scheduled rejuvenation time, even if some tasks are still processed. However, in practice, the possible chances to execute software rejuvenation are limited. In this paper, such possible timing is called *opportunity*. Examples of opportunity are planned outage and completion of a task. That is, trigger time of rejuvenation is not exactly same as the

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starting time of rejuvenation in practice.

Garg et al. [9] dealt with such problems by considering two different rejuvenation policies in a stochastic model for transaction-based system. They proposed the two rejuvenation policies; the rejuvenation is immediately performed at a scheduled time interval (Policy I) and the rejuvenation is started at which a queue of arriving jobs is empty (Policy II). Salfner and Wolter [10] considered three time-triggered rejuvenation policies including policies with opportunities in a queueing model. Avritzer et al. [11] also discussed the opportunities of rejuvenation in MANETs from qualitative points of view. Okamura et al. [12] discussed the optimality of the time-triggered rejuvenation in a similar queueing system by using Markov decision process and presented that there are the cases where the opportunity-based policies are needed. Apart from the software rejuvenation, Dekker and Dijkstra [13] discussed the opportunity-based age-replacement model, which is similar but different from the software rejuvenation model.

This paper discusses the condition on the existence of the optimal trigger time of rejuvenation under probabilistic opportunities. More precisely, we consider two general stochastic point processes; renewal process and Markovian arrival process (MAP) to represent opportunity occurrences. Under these opportunity processes, we find the existence condition on the optimal trigger time of rejuvenation in an existing software rejuvenation model proposed by [5]. Note that the opportunity-based software rejuvenation policy is a generalization of the rejuvenation policies discussed in [9] and [10].

The paper is organized as follows. In Sect. 2, we describe a basic software rejuvenation model and introduce the opportunity time-triggered software rejuvenation policy. Section 3 formulates the expected reward rate in the steady state as an optimization criterion. Furthermore, we derive the sufficient condition for the existence of the optimal rejuvenation time under the opportunity time-triggered software rejuvenation policy. In Sect. 4, we present a specific case of the theoretical result in Sect. 3 as the maximization problem by assuming the opportunity process as specific point processes. Section 5 is devoted to numerical examples for the opportunity time-triggered software rejuvenation policy. In particular, we present an illustrative example for the optimal design of rejuvenation trigger time from empirical data.

2. Model Description

Consider a software rejuvenation model proposed by Dohi et al. [5]. They presented an extended model from Huang et al. [14] by the semi-Markov modeling. The system is divided into the following four states:

- **State 0:** highly robust state (normal operation state)
- **State 1:** failure probable state
- **State 2:** failure state
- **State 3:** software rejuvenation state

Suppose that the system starts in the normal operation state at time $t = 0$. Let T_0 be a random time duration when the system is in the highly robust state, namely, the system goes to the failure probable state at the time instance T_0 due to software aging. The cumulative distribution function (c.d.f.) of T_0 is given by $P(T_0 \leq t) = F_0(t)$ with a finite mean $0 < \mu_0 < \infty$. Suzuki et al. [6] assumed that T_0 was unobservable and discussed the rejuvenation under such situation. In contrast, this paper assumes that T_0 is observable. The accurate estimation of T_0 is important to determine the software rejuvenation strategy. The essential difference between normal and failure probable states is the difference of failure rates. Although the detection of such a change of failure rate is difficult, Alonso et al. [8], for example, succeeded detecting the change point of system failure rate statistically by applying machine learning with observable system attributes such as memory usage.

According to the assumption, we consider the ordinary time-triggered software rejuvenation policy (TSRJ). Let t_0 be a scheduled trigger time of software rejuvenation. That is, if the sojourn time in the failure probable state reaches to t_0, the system executes the software rejuvenation operation immediately. Otherwise, if the system failure occurs before t_0, the system executes the recovery operation. Let T_f denote a failure time which is measured from the time instance when the system becomes the failure probable state, and T_f has a c.d.f. $P(T_f \leq t) = F_f(t)$. Then the sojourn time of the failure probable state is given by $min(T_f, t_0)$. Moreover, we define T_a and T_c be random variables representing recovery and rejuvenation operation times, whose c.d.f.'s are given by $P(T_a \leq t) = F_a(t)$ and $P(T_c \leq t) = F_c(t)$ with finite means $0 < \mu_a < \infty$ and $0 < \mu_c < \infty$, respectively. Figure 1 illustrates a state transition diagram of the semi-Markov model under TSRJ policy.

Based on the above original semi-Markov rejuvenation model, we consider an opportunity process. The opportunity means the time instance when the software rejuvenation is safely executed. For instance, the completion of the current task and the planned outage are concrete opportunities to execute the software rejuvenation without effect on the system task. In this situation, the rejuvenation is performed according to the following strategy:

- **Opportunity time-triggered rejuvenation policy (OTSRJ):** The rejuvenation operation starts at the first opportunity after the scheduled trigger time of rejuvenation t_0.

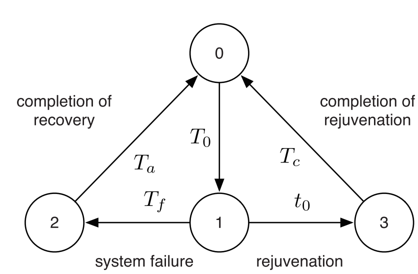

Fig. 1 State transition diagram of the basic rejuvenation model.

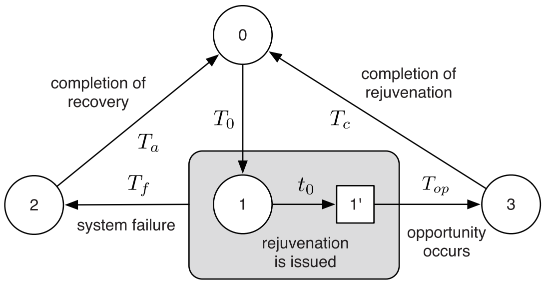

Fig. 2 State transition diagram of the opportunity-based rejuvenation model.

The OTSRJ policy is similar to opportunity-based rejuvenation policies discussed in [9] and [10], where the rejuvenation is performed when all the buffered tasks are completed in a transaction-based system. Under the OTSRJ policy, the state transition diagram can be depicted as Fig. 2. The software rejuvenation cannot be executed at which the sojourn time of failure probable state reaches to the scheduled trigger time of rejuvenation t_0, but the system state becomes State 1' (failure probable state and waiting for an opportunity), which is a regenerative point. If a system failure occurs in State 1', the recovery operation is performed immediately. Let T_{op} denote the interval between the trigger time and the first opportunity occurrence, which generally has a c.d.f. depending on t_0 namely $F_{op}(t; t_0)$.

3. Reward Analysis

Under OTSRJ policy, we consider the expected reward rate in the steady state. Let ξ_i, $i = 0, \ldots, 3$ be reward rates for respective system states $i = 0, \ldots, 3$, where the reward rate of state $1'$ is given by ξ_1. Define a cycle between two successive time points when the system becomes the highly robust state. Moreover, $R_{op}(t_0)$ and $L_{op}(t_0)$ are the expected total reward during one cycle and the expected time length of one cycle under OTSRJ policy with the rejuvenation trigger time t_0, respectively. Then we have

$$\begin{aligned} R_{op}(t_0) = \xi_0\mu_0 + \int_0^\infty \Big(\xi_1 \int_0^{t_0+s} \overline{F}_f(t)dt \\ + \xi_2\mu_a F_f(t_0+s) + \xi_3\mu_c\overline{F}_f(t_0+s)\Big)dF_{op}(s; t_0) \end{aligned} \quad (1)$$

and

$$\begin{aligned} L_{op}(t_0) = \mu_0 + \int_0^\infty \Big(\int_0^{t_0+s} \overline{F}_f(t)dt \\ + \mu_a F_f(t_0+s) + \mu_c\overline{F}_f(t_0+s)\Big)dF_{op}(s; t_0), \end{aligned} \quad (2)$$

where in general $\overline{F}(t) = 1 - F(t)$. Based on the renewal reward theorem [15], we get the expected reward rate in the steady state as follows.

$$\begin{aligned} RR(t_0) &= \lim_{t\to\infty} \frac{\mathrm{E}[\text{the cumulative reward during } [0,t)]}{t} \\ &= \frac{R_{op}(t_0)}{L_{op}(t_0)}. \end{aligned} \quad (3)$$

Suppose that the failure distribution $F_f(t)$ is differentiable at any point, i.e., the probability density function (p.d.f.) $f_f(t) = dF_f(t)/dt$ exists. Define the following function:

$$\begin{aligned} q(t_0) = \Big(\xi_1 + (\xi_2\mu_a - \xi_3\mu_c)\psi_{op}(t_0)\Big)L_{op}(t_0) \\ + \Big(1 + (\mu_a - \mu_c)\psi_{op}(t_0)\Big)R_{op}(t_0), \end{aligned} \quad (4)$$

where

$$\psi_{op}(t_0) = \frac{\int_0^\infty f_f(t_0+s)dF_{op}(s; t_0)}{\int_0^\infty \overline{F}_f(t_0+s)dF_{op}(s; t_0)}. \quad (5)$$

Then the sign of the above function $q(t_0)$ equals the sign of the first derivative of $RR(t_0)$ with respect to t_0. By using the function $q(t_0)$, we obtain the theoretical result on the existence of the optimal trigger time which maximizes the expected reward rate under OTSRJ policy. Here we consider two assumptions:

- **A-1:**

$$\mu_a > \mu_c, \quad (6)$$

- **A-2:**

$$(\xi_3 - RR(t_0))\mu_c > (\xi_2 - RR(t_0))\mu_a \quad \text{for } 0 \le t_0 < \infty. \quad (7)$$

The assumption A-1 means that the expected execution time of rejuvenation is less than the expected time of recovery operation, and it holds in many practical situations. On the other hand, the assumption A-2 indicates almost same meaning as the expected reward earned by the rejuvenation is greater than that by the recovery operation. The assumption A-2 does not always hold in all the cases. However, it is not difficult to prove that the assumption A-2 holds in some specific cases [5]. Under these assumptions, we have the following theorem:

Theorem 1: Suppose that the assumptions A-1 and A-2 hold.

- **Case I:** $\psi_{op}(t_0)$ is a strictly increasing function with respect to t_0.
  - If $q(0) > 0$ and $q(\infty) < 0$, then there exists the finite and unique optimal trigger time of rejuvenation t_0^* such that $q(t_0) = 0$, and the maximum expected reward rate is given by

$$RR(t_0^*) = \frac{\xi_1 + (\xi_2\mu_a - \xi_3\mu_c)\psi_{op}(t_0^*)}{1 + (\mu_a - \mu_c)\psi_{op}(t_0^*)}. \quad (8)$$

  - If $q(0) \le 0$, then the optimal trigger time of rejuvenation is given by $t_0^* = 0$, namely, it is optimal to start the rejuvenation whenever the system becomes the failure probable state.
  - If $q(\infty) \ge 0$, then the optimal trigger time of rejuvenation is given by $t_0^* \to \infty$, namely, it is optimal

not to carry out the rejuvenation.

- **Case II:** $\psi_{op}(t_0)$ is a decreasing function with respect to t_0. The optimal trigger time of rejuvenation is given by $t_0^* = 0$ or $t_0^* \to \infty$.

The proof of Theorem 1 is given in Appendix.

4. Special Opportunity Processes

4.1 Renewal Process

In this section, we derive a sufficient condition for the existence of the optimal trigger time maximizing the expected reward in the steady state under specific opportunity processes. First we consider a renewal process. The renewal process is a well-known point process where the time interval of event occurrences follows a general distribution.

Let $0 = X_0 < X_1, < X_2, \ldots$ be an opportunity time sequence where X_i is the i-th opportunity occurrence. Suppose that $X_i - X_{i-1}$, $i = 1, 2, \ldots$ are independent and identically distributed (i.i.d.) random variables with the c.d.f. $G(t)$. In this paper, we consider the following two cases for the starting time of the system:

- (i) Synchronized: The recovery and rejuvenation renew the opportunity process. That is, the staring time of system and opportunity process are synchronized.
- (ii) Independent: The system behavior is independent to the opportunity process.

The synchronized case represents the situation where the opportunity is also refreshed (renewed) by rejuvenation and recovery operations. For these two cases, we obtain c.d.f.'s of the first opportunity time as follows.

- Synchronized:

$$F_{op}^{(i)}(s; t_0) = G(t_0 + s) - \int_0^{t_0} \overline{G}(t_0 + s - t) dM(t), \tag{9}$$

- Independent:

$$F_{op}^{(ii)}(s; t_0) = \frac{1}{\mathrm{E}[X_i - X_{i-1}]} \int_0^s \overline{G}(t) dt, \tag{10}$$

where $M(t)$ is a renewal function representing the expected number of event occurrences during $[0, t)$. In general, the renewal function can be derived by solving the following renewal equation:

$$M(t) = G(t) + \int_0^t M(t - s) dG(s). \tag{11}$$

Eqs. (9) and (10) correspond to the c.d.f. of a residual life time and the equilibrium distribution in the renewal process theory [16]. In particular, the equilibrium distribution is a limiting distribution from the residual life time distribution, i.e.,

$$F_{op}^{(ii)}(s; t_0) = \lim_{t_0 \to \infty} F_{op}^{(i)}(s; t_0). \tag{12}$$

It should be noted that the equilibrium distribution does not include the parameter t_0.

In the Independent case, we have the following result:

Proposition 1: Suppose that $F_{op}(s; t_0)$ is the equilibrium distribution given in Eq. (10). If $F_f(t)$ has a strictly increasing failure rate (IFR) property, then $\psi_{op}(t_0)$ becomes a strictly increasing function.

The proof of Proposition 1 is given in Appendix. By combing Theorem 1 and Proposition 1, we find that there exists the optimal trigger time of rejuvenation which maximizes the expected reward if the failure time distribution has the IFR property in the case where the opportunity process is independent of the system behavior. In other words, the sufficient condition for the existence of the optimal trigger time under OTSRJ policy in the Independent case is essentially same as the condition under TSRJ policy discussed in [5].

4.2 Markovian Arrival Process

Although the renewal process can represent the opportunity occurrences whose time interval follows an identical general distribution, we often encounter the situation where the inter-arrival time of opportunities cannot be identical. For example, if the opportunity is given as the time when applying patches or system updates, it is not clear that the time intervals are identical. Then we also consider another point process called Markovian arrival process (MAP) as an opportunity process.

MAP is a point process whose event occurrence rate is dominated by a continuous-time Markov chain (CTMC). The CTMC states correspond to internal states to determine the event occurrence rates, and the CTMC state is called a phase in this paper. Let $\boldsymbol{D}_0$ and $\boldsymbol{D}_1$ denote the m-by-m infinitesimal generators of the underlying CTMC without and with opportunities. That is, $\boldsymbol{D}_0$ represents the phase transitions without opportunities in the CTMC, and $\boldsymbol{D}_1$ is the phase transitions with opportunity occurrences. Concretely, two infinitesimal generators are given by

$$\boldsymbol{D}_0 = \begin{pmatrix} -\mu_{1,1} & \mu_{1,2} & \cdots & \mu_{1,m} \\ \mu_{2,1} & -\mu_{2,2} & \cdots & \mu_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{m,1} & \mu_{m,2} & \cdots & -\mu_{m,m} \end{pmatrix}, \tag{13}$$

$$\boldsymbol{D}_1 = \begin{pmatrix} \lambda_{1,1} & \lambda_{1,2} & \cdots & \lambda_{1,m} \\ \lambda_{2,1} & \lambda_{2,2} & \cdots & \lambda_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{m,1} & \lambda_{m,2} & \cdots & \lambda_{m,m} \end{pmatrix}, \tag{14}$$

where $\mu_{i,i} = \sum_{j=1, j \neq i}^{m} \mu_{i,j} + \sum_{j=1}^{m} \lambda_{i,j}$. It should be noted that the infinitesimal generator of the underlying CTMC process (phase process) is given by $\boldsymbol{D}_0 + \boldsymbol{D}_1$. The initial phase at $t = 0$ is determined by an initial probability vector $\boldsymbol{\pi} = (\pi_1, \pi_2, \ldots, \pi_m)$ with $\boldsymbol{\pi e} = 1$, where $\boldsymbol{e}$ is a column vector with all elements equal to 1.

The MAP includes several important point process such as homogeneous Poisson process, Markov-modulated Poisson process (MMPP) [17] and phase renewal process. Also it is well known that the MAP can approximate any point process with any precision if the number of phases is unlimited [18].

Similar to the case of renewal process, we consider two cases, Synchronized and Independent for the correlation between the system operation and opportunity process.

- (iii) Synchronized: The rejuvenation (recovery) operation resets the opportunity process.
- (iv) Independent: The opportunity process is independent of the system behavior.

According to the argument of MAP, we have the first opportunity time distribution after the rejuvenation trigger time t_0 in the MAP case:

- Synchronized:

$$F_{op}^{(iii)}(s;t_0) = 1 - \pi \exp\left((\boldsymbol{D}_0 + \boldsymbol{D}_1)t_0\right) \exp(\boldsymbol{D}_0 s)\boldsymbol{e}, \tag{15}$$

- Independent:

$$F_{op}^{(iv)}(s;t_0) = 1 - \pi_s \exp(\boldsymbol{D}_0 s)\boldsymbol{e}, \tag{16}$$

where π_s is a stationary distribution satisfying $\pi_s(\boldsymbol{D}_0+\boldsymbol{D}_1) = \boldsymbol{0}$. It can be found that the relationship between Eq. (15) and Eq. (16):

$$F_{op}^{(iv)}(s;t_0) = \lim_{t_0\to\infty} F_{op}^{(iii)}(s;t_0). \tag{17}$$

Although the inter-arrival time distribution of MAP is not an identical distribution, the first opportunity time distribution in the steady state has the similar property as the equilibrium distribution. Here we obtain the following proposition:

Proposition 2: Suppose that $F_{op}(s;t_0)$ is given by Eq. (16). If $F_f(t)$ has a strictly increasing failure rate (IFR) property, then $\psi_{op}(t_0)$ becomes a strictly increasing function.

The proof of Proposition 2 is also given in Appendix. In the case where the opportunity process follows an MAP and it is independent of the system behavior, there exists the optimal trigger time of rejuvenation if the failure time distribution has the IFR property.

5. Numerical Examples

5.1 Renewal Process Case

We first investigate the effect of opportunity process on the optimal rejuvenation trigger time. Consider the maximization of system availability, i.e., the rewards are given by

$$\xi_0 = \xi_1 = 1 \quad \text{and} \quad \xi_2 = \xi_3 = 0. \tag{18}$$

It is straightforward to see that the Assumption A-2 is reduced to the Assumption A-1 in this case. In addition, we set $\mu_0 = 10.0$ (mean time to failure probable state), $\mu_a = 1.0$ (mean time to recovery) and $\mu_c = 0.5$ (mean time to rejuvenation). The failure time distribution is assumed to be the following gamma distribution

$$F_f(t) = \int_0^t \frac{\beta_f^{\alpha_f} s^{\alpha_f - 1} e^{-\beta_f s}}{\Gamma(\alpha_f)} ds, \tag{19}$$

where $\Gamma(\cdot)$ is the gamma function. Also α_f and β_f are shape and rate (scale) parameters of the gamma distribution, respectively, which are determined as $\alpha = 2.0$ and $\beta = 0.2$ so that the mean time to failure is 10.0 and the coefficient of variation (CV) is 0.5. The CV represents the uncertainty of distribution. As the CV is close to 0, the distribution gets close to a constant, i.e., the uncertainty decreases. Also, the CV of exponential distribution becomes 1 which is a suitable guideline to evaluate the uncertainty of distribution. The opportunity process is assumed to be a renewal process whose inter-arrival time distribution is given by the gamma function. The shape and scale parameters of inter-arrival time distribution are determined so that the mean time of an interval of opportunities is 2.0 and the CVs are 10.0, 2.0, 1.0, 0.5, 0.2 and 0.1.

Figure 3 illustrates the system availabilities with respect to the rejuvenation trigger time. In the figure, we assume that the renewal process is independent of the rejuvenation and recovery operations. Also, the line "no delay" indicates that the system availability when the rejuvenation can immediately be executed just after the rejuvenation trigger. Since $F_f(t)$ is the gamma distribution with the shape parameter $\alpha_f = 2.0$, the failure time distribution has an IFR property. As shown in the figure, there exists the optimal trigger time of rejuvenation which maximizes the system availability in all the cases. Table 1 presents the optimal rejuvenation trigger time and the maximum system availability. From these results, we find that the maximum system availability becomes greater as the CV is small. Since the distribution gets to a constant as the CV becomes small, the uncertainty of opportunity to execute rejuvenation strongly affects the performance of system in terms of system avail-

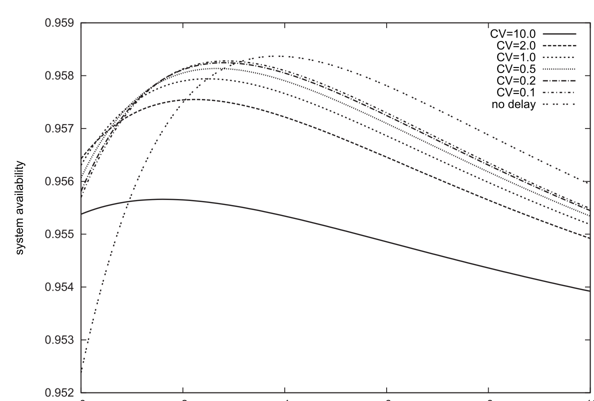

Fig. 3 System availabilities with respect to rejuvenation trigger time under OTSRJ.

Table 1 Optimal rejuvenation trigger time and maximum system availability under OTSRJ.

CV	Optimal rejuvenation trigger time	maximum system availability
10.0	1.6185	0.95566
2.0	2.2343	0.95755
1.0	2.4851	0.95794
0.5	2.6678	0.95814
0.2	2.8070	0.95824
0.1	2.8599	0.95828
no delay	3.8402	0.95837

Table 2 Patch release date of VMware ESXi 4.0.

Date	Patch ID
2009/5/21	(VMware ESXi 4.0 release)
2009/7/9	ESXi400-200906001
2009/8/6	ESXi400-200907001
2009/9/24	ESXi400-200909001
2009/11/27	ESXi-4.0.0-update01
2010/1/5	ESXi400-200912001
2010/3/3	ESXi400-201002001
2010/4/1	ESXi400-201003001
2010/5/27	ESXi400-201005001
2010/6/10	upgrade-from-esxi4.0-4.0_update02
2010/9/30	ESXi400-201009001
2011/1/4	ESXi400-201101001
2011/3/7	ESXi400-201103001
2011/4/28	ESXi400-201104001
2011/5/5	update-from-esxi4.0-4.0_update03
2011/10/13	ESXi400-201110001
2011/11/17	update-from-esxi4.0-4.0_update04
2012/3/30	ESXi400-201203001
2012/5/3	ESXi400-201205001
2012/6/14	ESXi400-201206001
2012/9/14	ESXi400-201209001

ability. Moreover, as the CV increases, the optimal rejuvenation trigger time becomes earlier. This implies that the rejuvenation policy is pessimistic in the case of the uncertain opportunity.

5.2 MAP Case

Next we illustrate the optimal rejuvenation design under OTSRJ by using MAP-based opportunity process with empirical data. In this example, we consider the virtualized platform that is commonly used in cloud computing. In the common situation, the virtualized platform provides the virtual environment where virtual machines run as continually running servers such as Web sever. That is, there are not many chances to perform the system rejuvenation because the rejuvenation of virtualized platform stops all the virtual machines on it. This example assumes that a candidate of opportunities for the rejuvenation is the time to execute system update or applying a patch.

Table 2 presents release date for security or critical patches of VMware ESXi 4.0. VMware ESXi is a representative system to provide the virtualized platform. The average and standard deviation of interval time of two patch releases are 60.6 (days) and 39.7 (days), respectively. According to [19], [20], we estimate MAP parameters from the

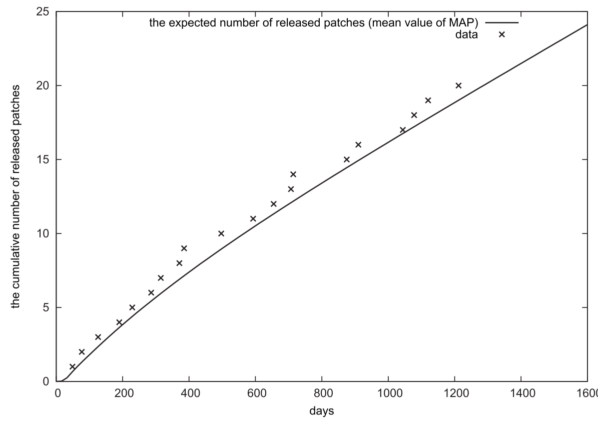

Fig. 4 The cumulative number of released patches.

Table 3 Model parameters of the virtualized platform [21].

Event	Mean Time
System aging (mean time to failure probable state)	1 month
System failure after aging (mean time to failure)	1 week
Completion time of recovery	1 hour
Completion time of rejuvenation	2 minutes

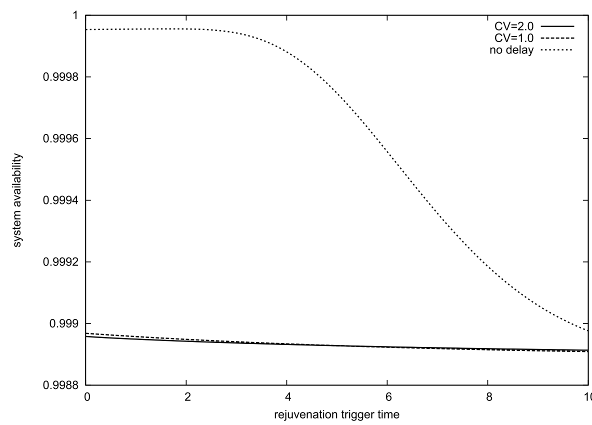

Fig. 5 System availabilities for the virtualized platform.

patch release data. Also, the number of phases of MAP was set as $m = 10$. Figure 4 draws the mean value of estimated MAP and the observed data as the cumulative number of released patches. The mean and standard deviation of a patch interval in the estimated MAP are given by 56.5 (days) and 52.0 (days), respectively.

Consider the maximization of system availability based on the estimated MAP. Clearly, the software rejuvenation of system does not affect the opportunity process defined by the process of patch releases. The model parameters of virtualized system are set as Table 3 which is cited from [21].

Similar to the case of renewal process, the failure time distribution is given by a gamma distribution with mean 1 week, and we vary the CV of failure time distribution. Figure 5 illustrates the system availabilities with respect to the rejuvenation trigger time under OTSRJ. By comparison, we also draw the system availability when there is no delay between the rejuvenation trigger and operation ("no delay"). As seen in the figure, for all the cases, the optimal rejuvenation trigger time is 0. That is the optimal policy is that the rejuvenation is triggered at which the system goes to the failure probable state. However, compared to the system availability without opportunity, the system availability with opportunity is further degraded. This is because the patch release is relatively longer than the system aging. In this situation, since the opportunity occurrence is a rare event, the system has been failed in most cases though the rejuvenation is triggered when the system is aging immediately. From this analysis, we find that patch release timing is not appropriate opportunity for the rejuvenation and another rejuvenation opportunity is required.

6. Conclusion

In this paper, we have considered an opportunity time-triggered rejuvenation (OTSRJ) policy in the basic software rejuvenation model under probabilistic opportunities. The presented model and policy are a generalization of some existing condition-based rejuvenation policies. Based on the stochastic model, we have derived the existence condition for the optimal trigger time of rejuvenation under OTSRJ policy analytically. Also we have discussed the two different opportunity processes; renewal process and MAP. In the result, the aging property of the failure time distribution dominates the existence of the optimal trigger time of rejuvenation even in the environment where opportunities randomly arise. Moreover, we have presented two numerical examples for the optimal trigger time of rejuvenation under OTSRJ. Lessons learned from the numerical examples are (i) the system availability is degraded when opportunities are uncertain, (ii) the rejuvenation policy should be pessimistic when opportunities are uncertain, (iii) to find appropriate opportunities is practically significant to enhance the system availability under rejuvenation.

In future, we consider on-line estimation of the optimal trigger time of rejuvenation based on the proposed model and policies. In addition, we try to find the existence condition of the optimal trigger time of rejuvenation in the case where system behavior and opportunity process are synchronized.

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Appendix A: Proof of Theorem 1

Consider the first derivative of $q(t_0)$:

$$\frac{d}{dt_0}q(t_0) = \psi'_{op}(t_0)(\mu_a - \mu_c)L_{op}(t_0) \times \left(\frac{\xi_2\mu_a - \xi_3\mu_c}{\mu_a - \mu_c} - RR(t_0)\right), \tag{A·1}$$

where $\psi'_{op}(t_0)$ is the first derivative of $\psi_{op}(t_0)$. Under the assumptions A-1 and A-2, the sign of Eq. (A· 1) is dominated by the sign of $\psi'_{op}(t_0)$. Therefore, when $\psi'_{op}(t_0) > 0$, $q(0) < 0$ and $q(\infty) > 0$, there exists a unique value such that $q(t_0^*) = 0$. Since the sign of $q(t_0)$ equals the sign of the first derivative of $RR(t_0)$, t_0^* maximizes $RR(t_0)$. $RR(t_0^*)$ can be derived from the equation $q(t_0^*) = 0$ directly.

Appendix B: Proof of Proposition 1

From the integration by parts, we have

$$\int_0^\infty f_f(t_0 + s)dF_{op}(s; t_0) = f_{op}(0)\overline{F}_f(t_0) + \int_0^\infty \overline{F}_f(t_0 + s)\frac{d}{ds}f_{op}(s; t_0)ds. \tag{A·2}$$

Since the equilibrium distribution is defined by Eq. (10), we get

$$\int_0^\infty f_f(t_0 + s)dF_{op}(s; t_0) = \frac{1}{\mathrm{E}[T_i - T_{i-1}]}\left(\overline{F}_f(t_0) - \int_0^\infty \overline{F}_f(t_0 + s)dG(s)\right). \tag{A·3}$$

Then Eq. (5) is reduced to

$$\psi_{op}(t_0) = \frac{1 - \int_0^\infty \overline{F}_f(s \mid t_0)dG(s)}{\int_0^\infty \overline{F}_f(s \mid t_0)dF_{op}(s)}, \tag{A·4}$$

where $\overline{F}_f(s \mid t_0) = \overline{F}_f(t_0 + s)/\overline{F}_f(t_0)$. Since the equilibrium distribution is independent of t_0, we replace $F_{op}(s; t_0)$ with $F_{op}(s)$. From the result of Bryson and Siddiqui [23], when $F_f(t)$ has a strictly IFR property, $\overline{F}_f(s \mid t_0)$ is a strictly decreasing function with respect to t_0. Therefore, when $F_f(t)$ has a strictly IFR property, $\psi_{op}(t_0)$ is a strictly increasing function with respect to t_0.

Appendix C: Proof of Proposition 2

From the proof of Proposition 1, it is only necessary to proof that the p.d.f. of Eq. (16) is a decreasing function. The p.d.f. of Eq. (16) is given by

$$f_{op}(s) = \pi_s(-\boldsymbol{D}_0)\exp(\boldsymbol{D}_0 s)\boldsymbol{e}. \tag{A·5}$$

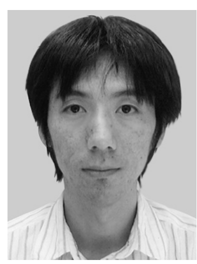
From $\pi_s(\boldsymbol{D}_0 + \boldsymbol{D}_1) = \boldsymbol{0}$, we have $\pi_s = \pi_s\boldsymbol{D}_1(-\boldsymbol{D}_0)^{-1}$. Then Eq. (A· 5) is reduced to

$$\begin{aligned} f_{op}(s) &= \pi_s\boldsymbol{D}_1(-\boldsymbol{D}_0)^{-1}(-\boldsymbol{D}_0)\exp(\boldsymbol{D}_0 s)\boldsymbol{e} \\ &= \pi_s\boldsymbol{D}_1\exp(\boldsymbol{D}_0 s)\boldsymbol{e} \\ &= \pi_s\boldsymbol{D}_1\boldsymbol{e}\frac{\pi_s\boldsymbol{D}_1}{\pi_s\boldsymbol{D}_1\boldsymbol{e}}\exp(\boldsymbol{D}_0 s)\boldsymbol{e}. \end{aligned} \tag{A·6}$$

Letting $\pi_d = \pi_s\boldsymbol{D}_1/\pi_s\boldsymbol{D}_1\boldsymbol{e}$, the vector holds

$$\pi_d = \pi_d(-\boldsymbol{D}_0)^{-1}\boldsymbol{D}_1. \tag{A·7}$$

Here $(-\boldsymbol{D}_0)^{-1}\boldsymbol{D}_1$ is a transition probability matrix of embedded discrete-time Markov chain on event occurrence points. Thus π_d is also the state probability vector. Since $\pi_d\exp(\boldsymbol{D}_0)\boldsymbol{e}$ is a complementary c.d.f. of a phase-type distribution, the p.d.f. of Eq. (16) is a decreasing function with respect to s.



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